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Blinks, Saccades, and Fixation Pauses During Vigilance Task Performance: I. Time on Task

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16. Abstract

In the future, operators of complex equipment will spend more time monitoring computer controlled devices rather than having hands-on control of such equipment. The operator intervenes in system operation under "unusual" conditions or when there is a computer malfunction. The latter occurs relatively seldom. The operator's task thus becomes a "vigilance" task, one requiring attention to monitoring equipment with little need for action. An individual's ability to maintain vigilance is easily compromised, with time-on-task (TOT) a major detractor of performance. The question asked in this research was: Can gaze control measures be used to reflect, and hopefully to predict, periods of impaired vigilance?

The results of this study clearly demonstrate that a number of aspects of eye movements and eye blinks show significant TOT effects. These effects are, we believe, more likely to be associated with short periods of attentional lapses or "microsleep" than with more tonic changes in alertness level. The literature dealing with such measures as indicants of "fatigue" and/or "time-on-task" effects is reviewed in considerable detail.

The study evaluated aspects of blinking and eye movements in subjects performing the Thackray and Touchstone ATC simulation task. Subjects performed the task for a 2-hour period on 3 separate occasions. Significant increases in blink frequency, blink closing duration, blink flurries, eye closures and fixation pause were obtained as well as similar effects for derivative measures.

Though the current data was collected through electrodes attached to the participant, much of the information can be acquired with remote monitoring technologies. This makes possible the application of such measures in a field setting where subjects are required to work on a display terminal.

Additional exploration of this approach and the new technologies should provide the information needed to develop strategies and approaches that will enhance operator reliability.

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BLINKS, SACCADES, AND FIXATION PAUSES DURING VIGILANCE TASK PERFORMANCE: I. TIME ON TASK

INTRODUCTION

It has long been our conviction, reinforced by a modicum of data, that the gaze control system should reflect time-on-task (TOT) or "fatigue" effects. The literature on which that conviction is based is, at best, spotty. A variety of occulometric measures have been tested for their ability to detect "fatigue" effects and most have been found wanting with respect to reliably demonstrating such effects. For example, the literature on Critical Flicker Fusion Frequency (CFF) as a measure of fatigue finds more studies claiming the absence of an effect than those which report a decrease in CFF as a function of "fatigue." Similarly, steady state high frequency brain evoked responses (i.e., the brain, especially the visual cortex is "driven" at the frequency or harmonic frequency of the flashed light) to sinusoidally-(or other waveform) modulated light have occasionally shown a reduction in the peak frequency at which such "driving" occurs, but again the literature is weighted in favor of not finding significant TOT effects. (TOT and "fatigue" effects will be used synonymously.)

We contend that TOT effects are best measured while performing the task on which the subject has been "fatigued." Bartlett (1943), whom we will quote more fully later, indicated that any change in the nature of the task a subject is required to perform will produce a return to normal, or better than normal, responding. The fact that recovery from "fatigue" is rapid has been known for many years, but not appreciated by many investigators who have studied fatigue effects by evaluating, for example changes in CFF as a function of interposed "work." Manzer (1927) reported on recovery from muscular fatigue and found that after 5 minutes of rest (following the flexing of various muscle groups to "exhaustion") recovery was up to 82% of original level, after 10 minutes 90%, and after 20 minutes, 95%.

Bills and McTeer (1932) report that recovery from fatigue induced by specific task performance is a function of similarity between the condition under which fatigue was induced and the task in which the effect of fatigue is evaluated. The more dissimilar the tasks, the greater the recovery.

Thus, a 2- or 5-minute CFF task administered seconds or minutes after the end of an exhausting 8-hour work day may not show any changes in CFF. Many researchers dealing with aspects of visual activity have reported that a relatively slight change in an experimental situation produced marked changes in the variable under investigation. Ponder and Kennedy (1927) have done this, for example, for eye blink frequency. ***Thus, we believe that the optimal strategy for demonstrating TOT effects is to record biological variables while the subject is performing the task.*** A second constraint we imposed in much of our research on aspects of vigilance is that we wanted to utilize measures which, if proved useful in simulation environments, could be readily transferred to field settings. It is our contention that techniques which remain dependent on the application of electrodes are not acceptable in field settings both because of technical skills required for the application of electrodes and non-acceptance of attachment of electrodes on the part of operators.

Thus, rather than recording brain activity (because we are interested in mental "fatigue" and the brain is presumably the place where such fatigue would be best manifested), which for the foreseeable future will require the application of electrodes to the scalp, we selected gaze control variables and the eye blink. Many components of such variables can be recorded without the application of electrodes. Another concern was with "ecological validity." It seemed to us that the air traffic controller's task, and the task utilized in the present study are visually demanding.

Measures that reflect what the eyes are doing would seem to be relevant in generating useful information in subjects performing such tasks for extended periods of time.

Our prior research has demonstrated that both frequency and other components of blinking are sensitive to task demands and TOT manipulations (Orchard & Stern, 1991; Fogarty & Stern, 1989; Goldstein, Bauer & Stern, 1992; Stern, Beideman & Chen, 1976; Stern & Skelly, 1984). We were thus reasonably sanguine about demonstrating such effects in the present context. Regarding saccadic eye movements, fixation pauses, other eye movements, and head movements, the results from the literature were less reassuring. However, we, as well as others, have demonstrated drug as well as "fatigue" induced reductions in saccade duration and velocity, and an increase in long duration fixation pauses in situations requiring frequent gaze shifts. Others have supported the idea that head movements might reflect aspects of task difficulty. We thus believed that these measures would also be sensitive to TOT demands.

A note of caution should be voiced here. Thackray and Touchstone (1989) videotaped subjects performing a task very similar to the one used in the current investigation. They analyzed the videotapes to determine if aspects of gaze were predictive of why a subject missed a "critical" event. Thackray and Touchstone were not able to identify any differences in eye activity during periods where signals were missed in comparison with periods of appropriate responding.

With 20/20 hindsight, we have no problem accounting for the negative results reported by Thackray and Touchstone. Signals most likely to be missed and those which increased the likelihood of being missed, were restricted to those in which two aircraft were identified as flying at the same altitude, and were flying either toward or away from each other. The operator first had to identify that both were at the same altitude. This requires the subject to remember altitude information for as many as seven aircraft at a time, and to determine which two were at the same altitude. It is thus quite possible that the operator sequentially looked at all 8 aircraft but forgot altitude information about those early in the sequence by the time he reached the later aircraft. The eye movements under such conditions may well be appropriate, but the operator still does not respond. Shifting gaze to a location is not equivalent to abstracting information from that location, nor is it indicative of remembering information abstracted for even a second or two.

In the current study, our initial concern was not with being able to identify gaze control inefficiencies specifically associated with missed signals, but with changes in such variables as a function of TOT. We suspect that some, but not all missed signals, are associated with gaze control inefficiencies. We are also convinced that if an event to which a rapid response is required occurs concurrent with a period of gaze control inefficiency, the likelihood is great that the response to that signal will be inappropriate or that no response will be made. We thus wish to suggest that most, if not all, gaze control inefficiencies when they occur concurrent with the need to detect and process infrequently occurring information will lead to inappropriate responding. The converse is not true; inappropriate responses can occur in the absence of gaze abnormalities.

What do we mean by "gaze control inefficiencies," a concept we have introduced a number of times above? We are now on shaky ground and, to mix metaphors, will climb out on a limb and identify some possible measures.

a. eye blink

   Eye blink frequency is related to the visual demandingness of a task. The average blink rate during reading is significantly lower than during rest. Thus an increase in blink rate during reading and other task performance might index such inefficiency.

   It is obvious that if an important event occurs during a limited time period and that period is occupied by a blink, the event in question will be missed when the lid is closed for a long as compared to a short period.

b. eye closures

   Eye closures are identified if lid reopening following a closure does not occur within one second. It is obvious that no visual information can be acquired if the eyes are closed.

c. eye movements - saccades

Saccade velocity or amplitude/duration relationships decrease as a function of a number of variables including TOT. Since information intake for a period preceding, during, and following a saccade is limited (saccade suppression), such intake is likely to be restricted for a longer period of time when saccade duration is extended.

d. head movement

Head movements are, we believe, less efficient ways to acquire information than the use of eye movements. Thus, an increase in head movements, as a function of TOT, might index a reduction in efficiency. It might also index discomfort on the part of the operator, another potential contributor to inefficient performance.

e. combinations of the above measures - for example, blinks and saccades.

Blinks and saccades generally occur in tight temporal relationship to each other. If blinks start appearing with greater frequency during fixation pauses, it might indicate inefficiency (since during a blink there is a period of non-seeing and during a saccade there is also a period of minimal information intake; if the 2 occur concurrently, there is a reduction in the time for which information is not available). If blinks are unlikely to occur as gaze is shifted from the CRT to the keyboard and are most likely to occur as gaze shifts back to the CRT, then the occurrence of blinks under the former condition might be interpreted as a sign of inefficiency.

These are some examples of gaze control inefficiency:

The model entertained by us to account for the increase in missed signals as a function of TOT is, in many respects, similar to that proposed many years ago by Bills (1931), and accounts for delayed or missed responses using the concept of "blocks." Bills demonstrated such "blocks" in subject-paced tasks. Others (Teichner, 1968) have extended the concept to more complex and not necessarily subject paced tasks. Stave (1977) described blocks in helicopter pilots flying a simulator for several hours. Others, Oswald (1962) and Williams, et al. (1959), have described similar blocks and invested them with the label "microsleep" or "daydreaming."

It is our contention that periods of microsleep and, perhaps, precursors to such periods, can be identified from a study of gaze control variables. We have in prior research, Stern, Goldstein and Walrath (1984) and Lobb and Stern (1986), demonstrated oculometric variables associated with the operator missing signals. Morris (1984) demonstrated a significant relationship between performance measures associated with flying a GAT-1 simulator for an extended period of time and aspects of blinking. This work was done in sleep deprived subjects and one might invoke the concept of microsleep to account for at least some of the results. Thus, gaze control measures may well be effective in demonstrating TOT effects and such effects may be related to performance deficits.

Whether speaking of blocks, microsleep or daydreaming, we suspect that during such periods attention is diverted away from the task at hand. Such periods of inattention to the task should be reflected in gaze control variables in tasks that are visually demanding. Visually demanding tasks require that major portions of the attentional "resources" available to the operator are focused on the task. Individuals thus have to inhibit attending to other aspects of the external or internal environment. It is our belief that the inability to maintain inhibitory control over attending to other sources of information leads to lapses in attention and that such lapses in focused attention on the task are reflected in "gaze control inefficiencies," some of which were described above.

METHODS

Subjects

Twenty subjects (14 male, 6 female), all paid for their participation, performed the aircraft (A/C) task (described below) on 3 separate occasions, 2 hours on each occasion. No subject had prior experience with the task or had been involved in Air Traffic Control (ATC) training.

Apparatus and task description

Equipment available to the subject included a 19-inch graphic display terminal, a keyboard attached to the lower right edge and in-line with the CRT, and a joystick. A VAX11/730 computer controlled the display and was used to abstract response information.

The task required subjects to continually monitor the CRT display. The display consisted of 2 nonintersecting vectors oriented from the lower right to the upper left side of the CRT. A small rectangle on the flight path defined location of an aircraft (A/C) with 8 A/C displayed on each vector. In an adjacent alphanumeric data block were displayed A/C identification, altitude and groundspeed. A/C position and change in alphanumeric information were updated every 6 seconds. The update was done by quadrant, rather than by vector, thus the displayed information seemed to be continually changing. Occasionally, a nontracked, unidentified A/C appeared on the CRT as a steady green triangle. Occasionally, an A/C lost altitude information, with the numbers reflecting altitude replaced by three Xs (XXX). Occasionally, 2 A/C on the same flight path were at the same altitude. If they were flying away from each other a control button had to be pressed and no further response was required. If, however, they were flying toward each other, the operator was required to press a "conflict" button and place a cursor over one of the A/C and request reassignment of altitude. If the operator did not detect these latter events within 28 seconds from onset, both a visual and auditory "conflict alert" occurred. The visual alert consisted of the 2 A/C targets at the same altitude flashing, the auditory alert presented concurrent with the visual one was a 600hz, 65dB tone pulsed at 2 per second. Forty-four such events were presented over the 2-hour period. The minimum interevent time was approximately 1.5 minutes; the maximum about 4 minutes. Background "noise" consisted of a recording of "normal" activities in an ATC facility.

EXPERIMENTAL PROCEDURES

Subjects were instructed about the task they were to perform. Task performance was for a 2-hour period. They were given a short practice session to familiarize them with the task, the nature of the alarms, etc. Rating scales dealing with feelings of attentiveness, tiredness, strain, boredom and irritation were administered both before and after the 2-hour run. At the end of the 2-hour run, additional rating scales relating to perceived task difficulty and amount of effort required to perform the task were completed.

Subjects were prepared for the recording of horizontal and vertical electrooculograpy by attaching AgAgCl electrodes to the outer canthi of both eyes for the recording of horizontal, and above and below the right eye for the recording of vertical eye movements and blinks. Inter-electrode impedance was generally below 10000 ohms. Where that was difficult to achieve, we made sure that the impedance between the electrode pair from which activity was recorded was approximately the same when measured against an indifferent electrode. Signals were amplified by special purpose amplifiers with high common mode rejection. Amplifier output was linear from DC to 100hz. The output of these amplifiers was fed into a Kyowa data logger. Head movements were recorded by placing the inner liner from a construction worker's helmet on the subject's head. A strip of balsa wood was attached to the liner with the rear of the strip approximately in line with the subject's shoulders. At the tip of the strip and oriented downward and sideways were 4 LEDs, 2 on each side. Photocell receptors were attached to the left and right shoulder, equidistant from the light source when the head was facing forward. Again, the sensors or the subject was positioned so that the sensors were equidistant from the light source with the subject looking straight ahead. The output of the photocells was appropriately amplified and combined to allow for the recording of head movements in the horizontal plane. The output of the head movement amplifier was also fed into the Kyowa data logger. Stimulus and response information was coded by assigning different voltage levels to the different stimuli and responses. These voltage changes were also recorded on the data logger.

The taped data were then digitized and 5-minute samples were obtained starting at minute 10, 30, 50, 70, 90, and 110. Data were sampled at either 200 or 100 hz with all analyses conducted on data sampled at 100 hz. Data analysis utilized a DEC minicomputer

and was done semiautomatically, in that a skilled analyst applied our computer based algorithms for detecting eye blinks and saccadic eye movements to the data and performed editing functions, as necessary.

Most editing involved the deletion of saccades not meeting our "eyeball" criteria for acceptance as saccades. Major reasons for rejecting computer- identified saccades were the occurrence of a burst of muscle artifact, in which the algorithm detected an occasional "saccade," and the identification of a slow eye movement as a saccade (compensatory, pursuit or skin potential change). Eye movements were only evaluated in the horizontal plane.

Editing of eyeblinks was a somewhat more involved process if the blink occurred in conjunction with a major eye (and head) movement in the vertical plane. Such movements occurred when gaze had to be shifted from the CRT to the response panel located to the right and on a level with the base of the CRT. Such movements also occurred with return of gaze to the CRT. Our algorithm for detecting blinks includes, in part, (as part of the algorithm) the instruction that if the voltage level following completion of eye closure does not return to half amplitude of the closure in a specified time period (300 msc.) to not consider that voltage change pattern as a blink. The computer thus did not identify many blinks associated with gaze shifts from the response panel to the CRT. (An upward rotation of the eyeball produces a voltage change in the same direction as a lid closure.) Eye position higher in the visual plane at the end of a blink than it was before blink initiation precluded this criterion from being met. These blinks were manually identified by setting blink initiation at the same voltage level obtained after the eyes reopened. These blinks were thus measured as smaller in amplitude and shorter in duration than was really the case.

Some aspects of eyelid motion were manually abstracted. One of the criteria for blink identification requires the operator to set limits to the time between half closure and half reopening. This limit was 300 msec. for this data analysis. If a closure-reopening was not identified on the basis of this criterion, and the above process took less than a second, the event was labeled a long closure duration blink (LCD blink) and independently logged on a data sheet. If the closure-reopening took more than a second and was accompanied by no horizontal eye movements or slow pendular eye movements, it was identified as a lid closure and its occurrence and approximate duration abstracted.

The editing process allows for the inspection of 1000 data points in any one channel. The data were thus edited in 10-second chunks, a time consuming but necessary procedure. Five consecutive minutes (or 30 ten second frames) of data were analyzed, the output of this analysis printed, and summary statistic printed. Data from the summary statistics were used for all analyses, except for the blink flurry analysis, and other analyses that incorporated manually edited information. The blink flurry analysis was manually abstracted from the computer print-out of the raw analyzed data.

Measures abstracted and hypotheses concerning change as a function of TOT:

Blink rate (average number of blinks per minute).
Hypothesis. Significant increase.

Blink closing duration (average time from blink initiation to full closure).
Hypothesis. Significant increase in blink closure duration.

50% window (average time from lid being half closed during closing portion of blink to reopening to same level).
Hypothesis. Significant increase.

LCD Blinks (blinks with 50% window measure between 200 and 500 msec.
Hypothesis. Increase in frequency of such blinks.

Frequency of flurries (a flurry was defined by the occurrence of 3 or more blinks in 3 consecutive seconds.
Hypothesis. None - post hoc measure

Percent of blinks that are part of a flurry. (Blinks that are part of a flurry divided by all blinks).
Hypothesis. None - post hoc analysis

Corrected blinks (total number of blinks minus those that are part of a flurry; each flurry was counted as 1 blink).
Hypothesis. None - post hoc analysis

Eye closures (frequency of closures in excess of 500 msec.
Hypothesis. Increase in frequency.

Saccade rate (average number of saccades per minute).
Hypothesis. Reduction in rate

Median fixation duration
Hypothesis. Increase in median fixation duration.

Median saccade amplitude
Hypothesis. None

Long duration fixation pause (fixation pauses equal to or longer than 2 seconds.
Hypothesis. Increase in frequency.

DATA ANALYSIS PROCEDURE

Data for the 9 blink/closure measures and 4 saccade/fixation measures were abstracted for the 20 subjects for whom all 3 days of data were available. Appendix B contains the averaged data for each subject whose results were utilized in this analysis. Each matrix consists of data from each of the 3 days for the 6 identified time blocks. Data analysis utilized ANOVA's. Table 1 summarizes the results for all analyses and Table 2 presents results of pairwise comparisons. The pairwise comparisons were limited to adjacent and the first and last time blocks (minutes 10-30, 30-50, 50-70, 70-90, 90-110 and 10-110). The results are summarized in Tables 1 and 2.

RESULTS

Blink Measures

The data from each blink measure (blink rate, blink closing duration, 50% blink window, blink amplitude, long closure duration blinks, flurries, percent of blinks that are part of a flurry, corrected blink rate, and eye closures) were subjected to a between-within-subjects factor ANOVA. The principal analysis used Gender as a between subject variable (N=20). An additional analysis was done for each measure using the Time of Day (AM vs PM) at which subjects were run as the between subjects factor (N=13). Time of day (TOD) and Gender (G) are, unfortunately, confounded in this study. For the 20 subjects for whom all 3 days of data are available, 5 of the 6 females were run exclusively in the afternoon and 6 of the 14 males were run exclusively in the morning. The remaining 7 subjects (1 female, 6 males) had trials both in the morning and afternoon. It is impossible, therefore, to disentangle Gender from the Time of Day factor. Table 3 presents this information in tabular form.

The within factors were Day (1, 2 and 3) and Time sample (5-minute blocks sampled at 10, 30, 50, 70, 90, and 110 minutes into the session- TOT). Gender, the between subjects factor, was significant for only 1 of the blink measures, namely the percent of blinks that were a part of a flurry. The result of each analysis was then subjected to the Greenhouse-Geisser adjustment to degrees of freedom. The reported F values are for this adjustment, except where specifically noted. Where main and interaction effects were significant, lower level ANOVA's and paired comparisons were made using the Scheffé criterion. Only those subjects for whom we had data for all 3 days were used in this analysis (20 of 26 subjects completed all 3 days).

Blink rate. Blink rate consists of frequency of blinks in each 5-minute block divided by 5 (blinks/minutes). It was hypothesized that blink rate would increase over time. A significant time-on-task main effect was found [$F(2.71, 48.86) = 8.03$, $p = .0008$]. Blink rate increased reliably over time, as seen in Fig. 1. The linear trend is significant at the .0017 level. Pairwise comparisons did not result in any significant time block to time block increases; the only significant comparison was between block 1 and block 6 [$F(1, 18) = 11.48$, $p = .003$].

There were no significant Gender main effects or interactions, but the blink rate for females was higher than that for males on the first and last day in all time samples, and in 5 of the 6 time blocks on Day 2, as

TABLE 1

SUMMARY OF ANOVA RESULTS

Gender N = 20 TOD N = 13	Main Effects Gender TOD	Day	TOT	Day x G Day x TOD	Interactions TOT x G TOX x TOD	Day x TOT	D x TOT x G D x TOT x TOD
Blink Rate	.20	.19	.0008	.14	.68	.14	.79
	.09	.27	.004	.15	.42	.14	.77
Blink Closing Duration	.39	.28	.03	.10	.36	.39	.76
	.04	.20	.03	.29	.59	.29	.04
50% Window	.48	.40	.002	.03	.66	.03	.20
	.71	.54	.02	.07	.52	.16	.21
Blink Amplitude	.61	.87	.23	.62	.31	.31	.38
	.84	.37	.13	.26	.74	.03*	.43
LCD Blinks	.39	.45	.56	.23	.41	.65	.70
	.92	.63	.46	.05	.23	.33	.60
Frequency of Flurries	.17	.59	.01	.22	.66	.01	.03
	.21	.36	.14	.08	.49	.10	.67
Percent of Blinks that are	.03	.81	.001	.48	.36	.01	.14
Part of a Flurry	.59	.37	.32	.37	.35	.35	.34
Corrected Blinks	.30	.10	.01	.15	.99	.11	.23
	.09	.12	.01	.22	.73	.49	.31
Eye Closures	.87	.20	.11	.02	.71	.18	.48
	.56	.07	.24	.08	.48	.87	.10
Saccade Rate	.90	.83	.0004	.57	.84	.90	.73
	.94	.87	.0001	.13	.42	.75	.50
Md FixationDuration	.99	.49	.04	.48	.32	.74	.36
	.81	.88	.004	.38	.59	.50	.68
MD Saccade Amplitude	.37	.70	.0000	.08	.28	.20	.28
	.03	.72	.0007	.37	.42	.14	.53
Long Duration Fix Pause	.96	.15	.05*	.45	.77	.45	.14
	.14	.14	.02	.15	.76	.44	.36

*Huynh-Feldt adjusted df

TABLE 2
PAIRWISE COMPARISONS OF TIME BLOCKS

	10 - 30	30 - 50	50 - 70	70 - 90	90 - 110	10 - 110
Blink Rate	.397	.071	.334	.089	.083	.003
Blink Closing	.007	.685	.380	.412	.221	.008
50% Window	.005	.197	.378	.368	.855	.005
Frequency of Flurries	.014	.140	.877	.280	.350	.001
% of Blinks that are a part of a Flurry	.001	.868	.934	.394	.138	.0001
Corrected Blink Rate	.556	.070	.418	.234	.643	.037
Saccade Rate	.059	.388	.975	.975	.014	.987
Saccade Amplitude	.273	.620	.000	.003	.057	.56
Median Fixation Duration	.128	.154	.131	.005	.005	.597
Long Duration Fix Pause	.089	.082	.623	.248	.039	.002

TABLE 3
NUMBER OF SUBJECTS PER TIME CONDITION (AM vs. PM)

		N		
Males	AM for 3 days	6		
Males	PM for 3 days	2		
Females	AM for 3 days	0		
Females	PM for 3 days	5		
Mixed	AM day 1: PM day 2 & 3	2	M	
	AM day 1 & 2; PM day 3	1	M	
	AM day 1 & 3; PM day 2	1	M	
	PM day 1 & 2; AM day 3	1	M	1 F
	PM day 1; AM day 2 & 3	1		
		N = 20		

FIGURE 1

BLINK RATE

N = 20

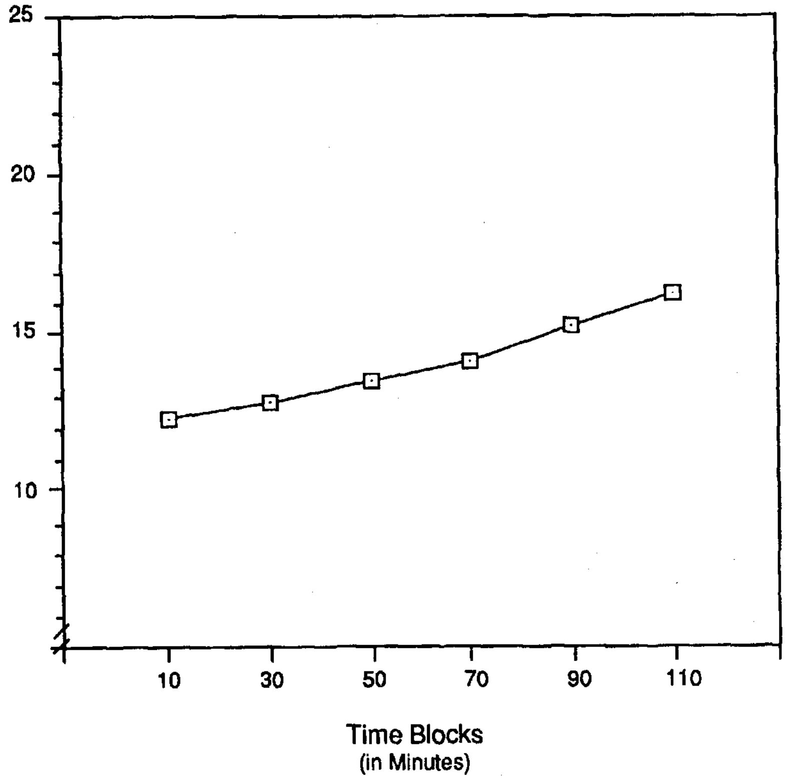


TABLE 4

MEAN BLINK RATE FOR MALES AND FEMALES FOR EACH TIME BLOCK FOR EACH DAY

BLINK RATE

	Day 1		Day 2		Day 3	
	Male	**Female**	**Male**	**Female**	**Male**	**Female**
Block 1	9.09	12.97	13.41	14.33	11.84	16.03
Block 2	10.10	13.30	12.46	13.78	12.31	19.43
Block 3	11.94	15.47	12.57	15.47	12.14	18.83
Block 4	11.37	14.70	14.53	16.90	12.71	19.33
Block 5	13.94	18.80	15.33	15.13	12.76	20.07
Block 6	13.47	19.40	16.16	18.66	14.11	21.47

shown in Table 4. The small sample sizes (Male N = 14 and Female N = 6) may be 1 reason for the lack of significant Gender effects.

The main effect of Day was not significant [$F(1.53, 27.48) = 1.82$ $p = 0.19$] nor were there any significant interactions. No TOD effects were significant.

Blink closing duration. Blink closing duration also increased reliably across time blocks [$F\ (3.09, 52.51) = 3.22$, $p = .03$] (Huynh-Feldt adjustment) as hypothesized. The linear trend is significant at the .02 level.

As seen in Fig. 2, blink closing duration increases substantially between the first time block (10 minutes) and the second time block (30 minutes) and stabilizes until the final block (110 minutes), where it again increases. The pairwise comparison for adjacent time blocks found a significant increase between blocks 1 and 2 [$F(1,17) = 9.27$, $p = .007$]. One female subject was excluded from this analysis because of missing data due to artifacts in recording the vertical channel.

There was no significant main effect of Day nor were there any significant interactions involving the Gender analysis. The main effect of Time of Day (TOD) was significant [$F(1,10) = 5.46$, $p = .04$] with morning mean blink closing durations considerably shorter than afternoon closing durations (AM Mean = 82.92 and PM Mean = 93.50). This main effect can be seen plotted across days, in Fig. 3.

The pattern of results is different for morning and afternoon subjects on each of the 3 days, as seen in Figs. 4a through 4c. This TOD X Day X TOT interaction is significant [$F(9.24, 92.43) = 2.08$, $p = .04$]. Average afternoon blink closing durations are longer than morning closing durations. The patterns for Day 1 and Day 2 increase over time. Day 3 morning closing durations follow a similar pattern as day 1 and day 2. Day 3 afternoon closing durations, on the other hand, show a slight increase over the first 3 time periods and then a sharp decrease at the third (50- minute) time block ending at a level lower than the closing duration of the first block.

Again, we must note that it is impossible to determine whether this is due to Time of Day or Gender, as these two factors are confounded.

Blink 50% window. A significant main effect of time on task for the 50% blink window was obtained [$F\ (3.31, 56.26) = 5.15$, $p = .002$]. As shown in Fig. 5, the 50% window increased significantly between the first block (at 10 minutes) and the second block (at 30 minutes). The paired comparison between block 1 and block 2 is significant at the .005 level [$F(1,17) = 10.60$, $p = .005$]. The 50% window duration then increased at a slower rate across the final 4 blocks, except for block 4, which represents the highest level. One female subject was excluded from this analysis because of missing data due to artifacts in recording. The linear trend is significant at the .005 level.

The main effect of the between-subjects factors, Gender, and TOD were not significant. There were, however, 2 significant interactions: Day X Gender [$F\ (1.95, 33.08) = 3.9$, $p = .031$] and Day X TOT [$F(5.36, 95.67) = 2.57$, $p = .03$]. The Day X Gender interaction, as seen in Fig. 6, shows the mean of the 50% blink window increasing steadily from Day 1 to Day 3 for males (N = 14), but the mean for females (N = 5) falls from Day 1 to Day 2, and then increases slightly on Day 3. Analysis of simple effects of Gender by day interaction found a significant effect for males [$F(1.96, 33.34) = 6.3$, $p = .005$]. Males showed the predicted pattern of increasing duration, while females did not. For females, a significant Day X TOT effect was found [$F(9.23, 156.84) = 2.04$, $p = .037$ (H-F)]. These results must be viewed in light of the Time of Day confound. It is impossible to determine which factor is responsible for the difference found in the 50% window measure across days - Gender or the Time of Day.

The Day X TOT interaction is shown in Fig. 7. The interaction depicted suggests that the 50% window measure asymptotes progressively earlier as we go from Day 1 to Day 3. The analysis of simple effects of day found a significant effect of Day at time block 1 [$F(1.9, 32.29) = 7.53$, $p = .002$]. In addition, the simple effects of Day X Gender at time 1 and time 2 were also significant. [$F(1.9, 32.29) = 4.77$, $p = .017$ and $F(1.88, 31.93 = 4.03$, $p = .027$, respectively].

Blink Amplitude. There were no significant main effects for the blink amplitude measure. There is, however, a Day X TOT interaction [$F\ (7.06, 70.63) = 2.31$, $p = .03$], for the subjects in the TOD analysis.

FIGURE 2
BLINK CLOSING DURATION

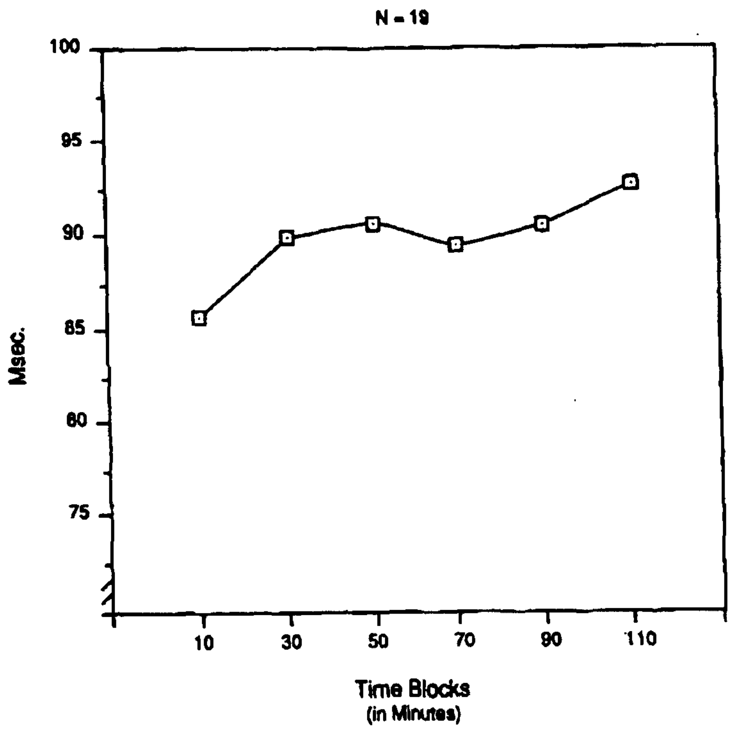


FIGURE 3
BLINK CLOSING DURATION

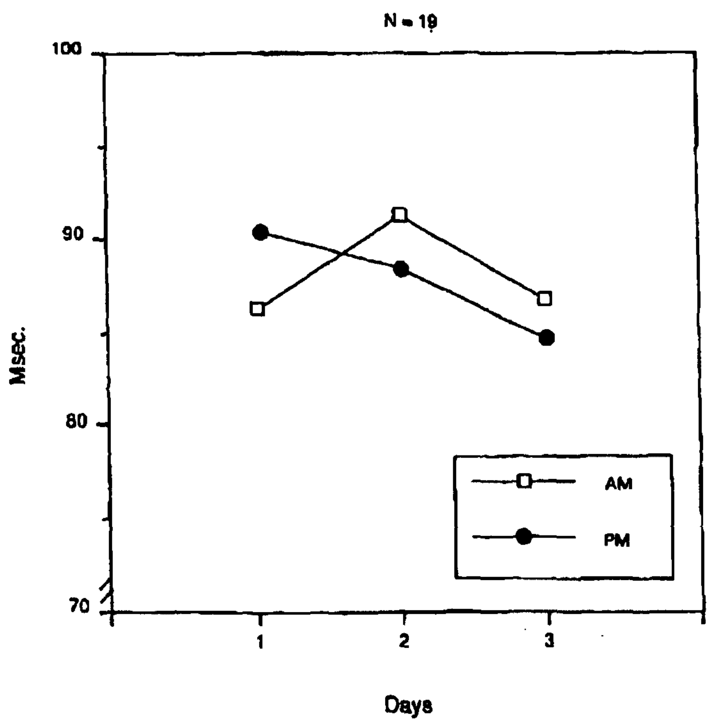


FIGURE 4A
BLINK CLOSING DURATION

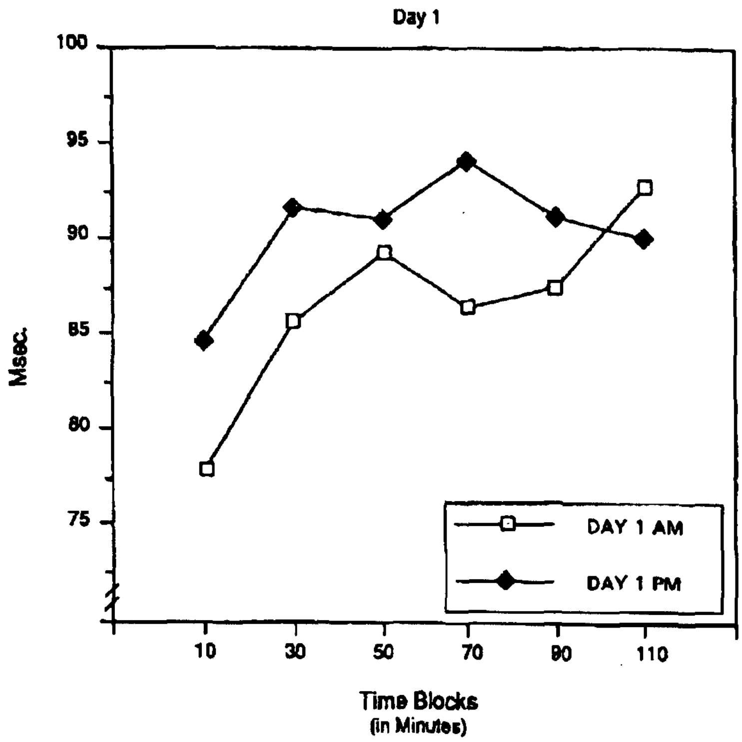


FIGURE 4B
BLINK CLOSING DURATION

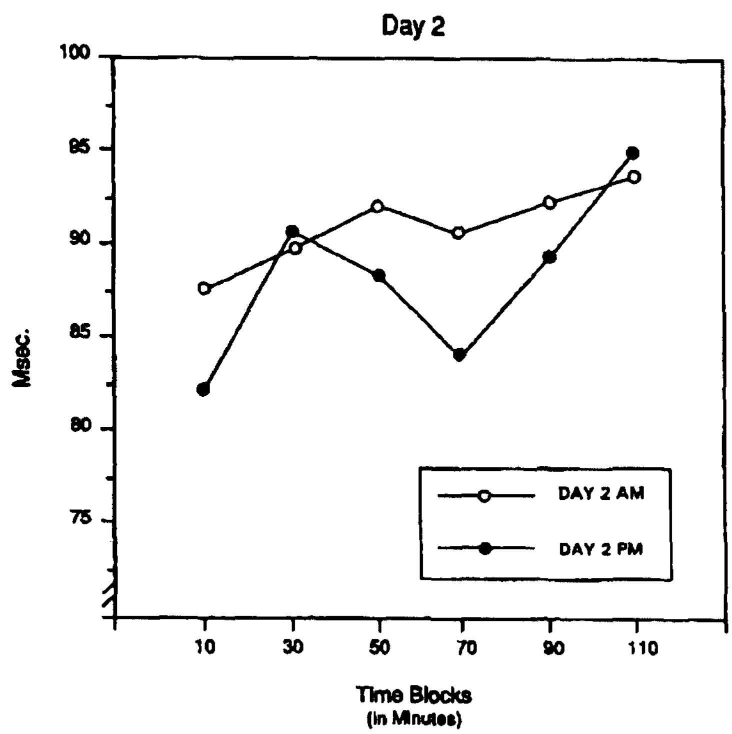


FIGURE 4C

BLINK CLOSING DURATION

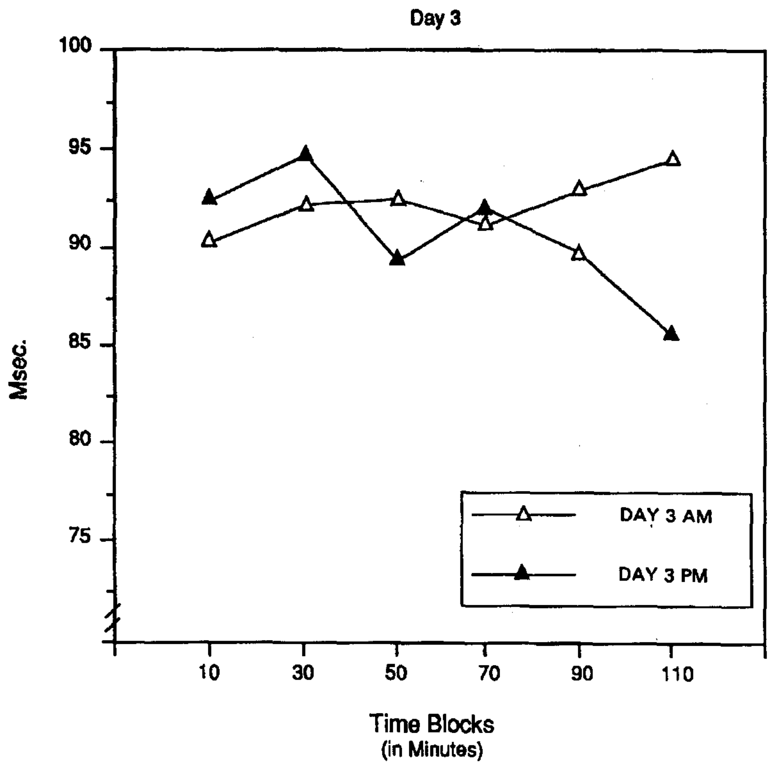


FIGURE 5

50% WINDOW

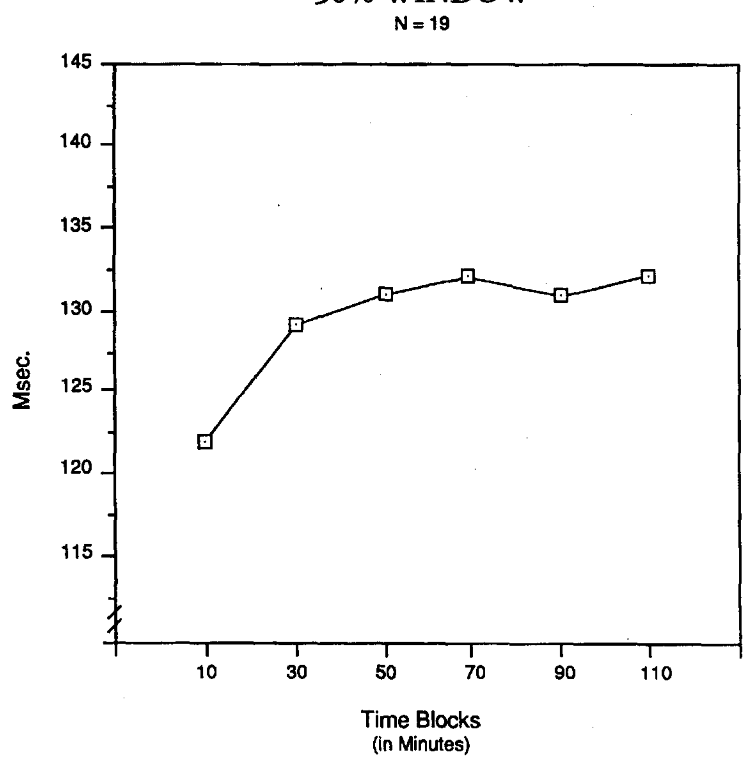


FIGURE 6

50% WINDOW

Day X Gender

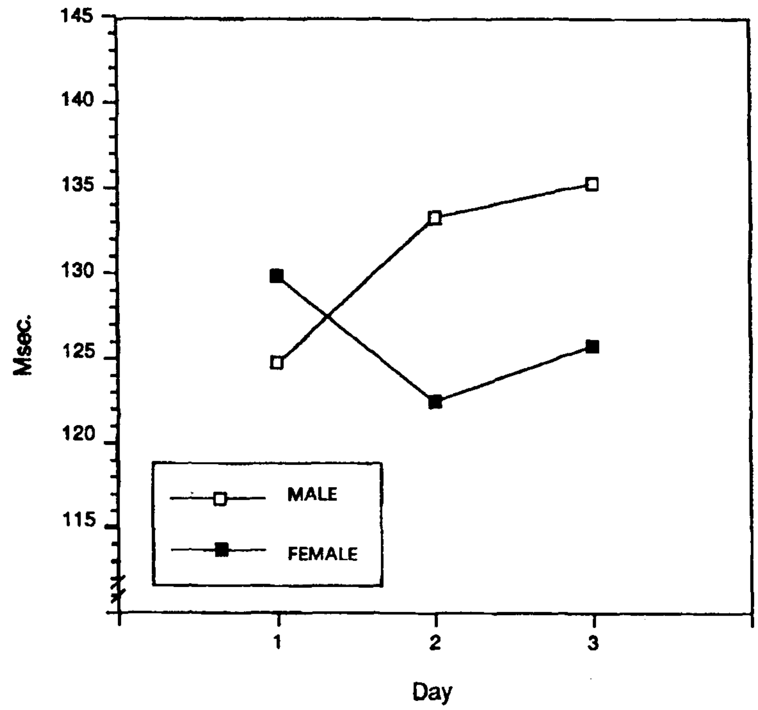


FIGURE 7

50% WINDOW

N = 19

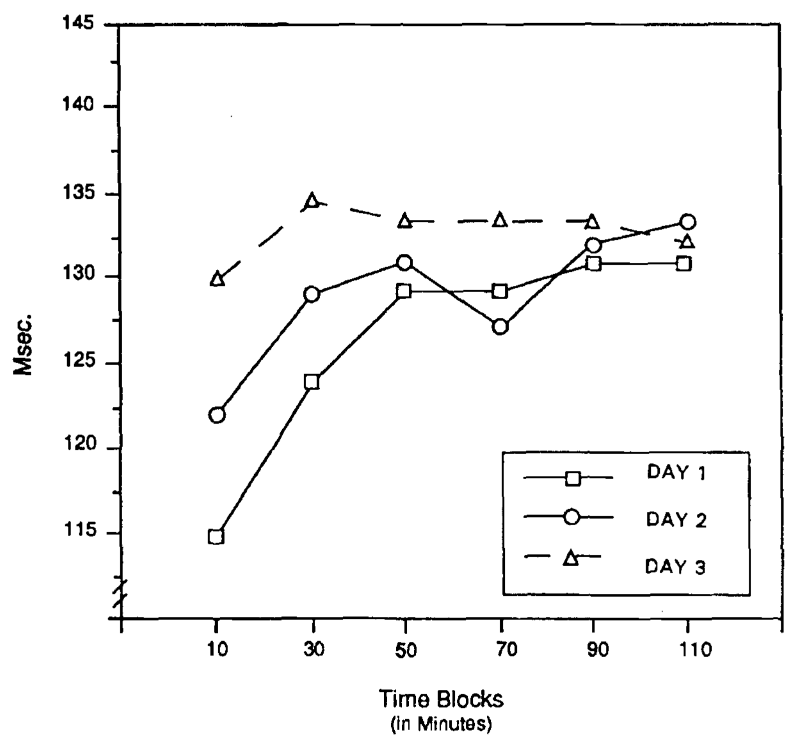
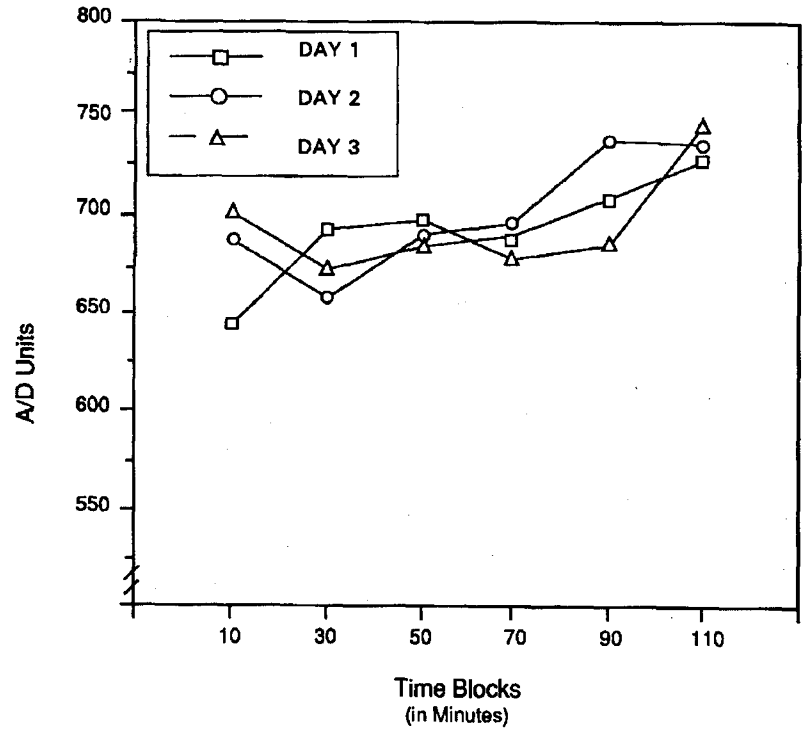


FIGURE 8
BLINK AMPLITUDE



Because the Day X TOT interaction was not significant for the Gender analysis, which included 19 subjects, we believe this to be a spurious result. As shown in Fig. 8, blink amplitude on Day 1 increased sharply from block 1 to block 2, while Day 2 and Day 3 blink amplitude decreased from block 1 through block 2.

Long Closure Duration Blinks. Long closure duration blinks are those blinks where the 50% window exceeds 200 msec. The analyses were performed on the total of manually abstracted LCD blinks (those greater than 300 msec), plus those tallied by the computer as being greater than 200 msec. expressed as a percentage of all blinks. There was a significant Day X TOD interaction [$F(1.8, 19.81) = 3.6$, $p = .05$]. As shown in Fig. 9, the mean AM percent of LCD blinks increased significantly from Day 1 to Day 3. Analysis of simple effect of TOD found this increase to be significant at the .03 level [$F(1.8, 19.81) = 4.46$, $p = .028$]. The afternoon subjects did not show an increase in LCD blinks. The percent of LCD blinks, in fact, remained constant from Day 1 to Day 2 and then decreased from Day 2 to Day 3. Again, the confound between TOD and Gender makes this result difficult to interpret, since it is impossible to determine which factor is responsible for the differences found.

There were no significant main effects for the long closure duration blink measure.

Flurries. Minimum criteria for a flurry required 3 or more blinks to occur within 3 seconds. A flurry could exceed 3 seconds. As long as succeeding seconds contained at least 1 blink, such blinks were considered part of the same flurry. There were 3 components to the flurry measure analyzed; a) frequency of flurries, b) percent of blinks that are a part of a flurry, and c) blink rate corrected for flurries.

FIGURE 9

LONG CLOSURE DURATION BLINKS

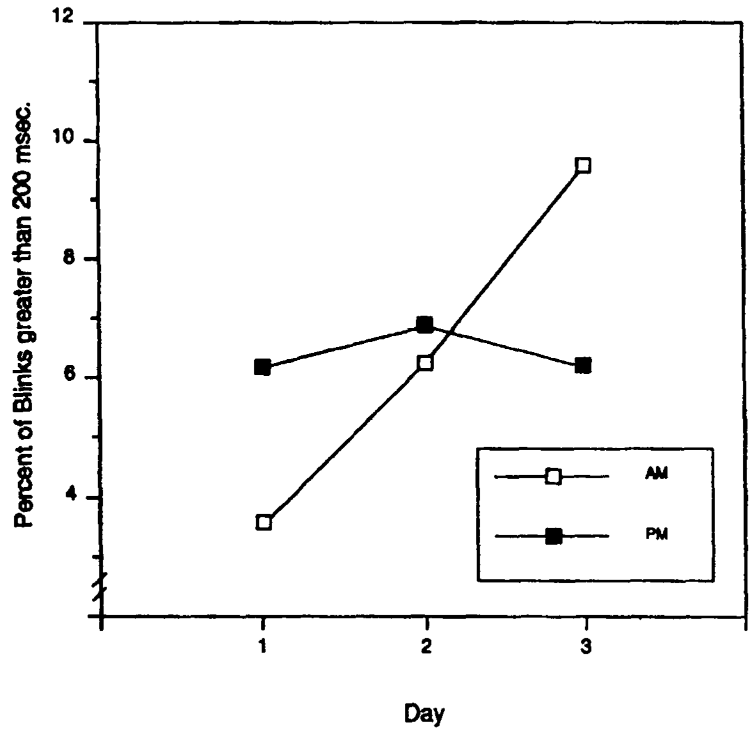


FIGURE 10

FREQUENCY OF FLURRIES

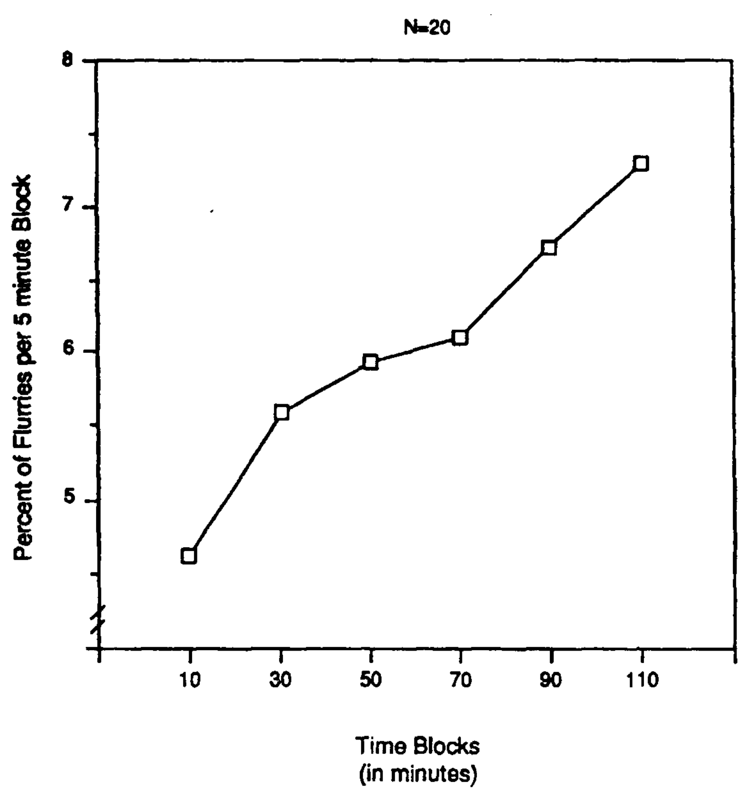
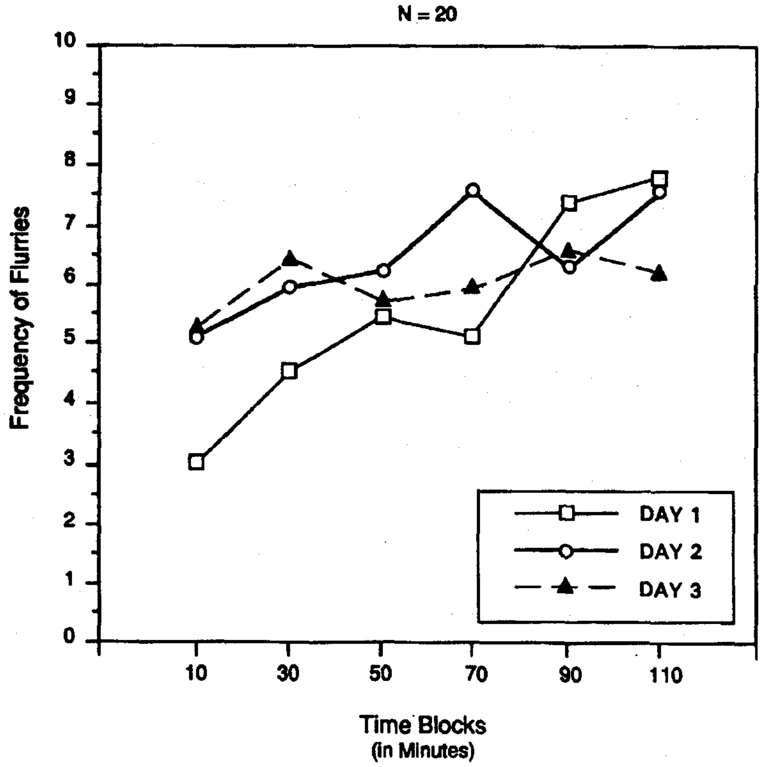


FIGURE 11

NUMBER OF FLURRIES OF BLINKS



Frequency of flurries. The frequency of an occurrence of flurries and the number of blinks contained in each flurry were tabulated manually. There was a significant TOT effect, [F(2.6, 46.76) = 4.51, p = .01], a significant Day X TOT interaction [F(5.59, 100.6) = 2.88, p =.01] and a significant 3-way interaction of Day X TOT X Gender [F(8.86, 159.41) = 2.10, p = .033] (H-F). The main effect of TOT, shown in Fig. 10, depicts a steady increase in the number of flurries. The paired comparison between block 1 and block 2 is significant at the .01 level [F(1,18) = 7.33, p = .01].

The Day X TOT interaction is depicted in Fig. 11. On Day 1, we see a significant increase from time block 1 to block 5 leveling off at 7.45 flurries per time block, except for block 4, which decreases slightly. Analysis of simple effects of TOT found the increase to be significant at the .001 level [F(2.37, 35.28) = 7.33, p = .001]. The pattern of blink flurries for Day 2 shows a similar pattern, but the increase is slower. Analysis of the simple effects of TOT were also significant for Day 2 [F(3.81, 68.67) = 2.62, p = .044]. On Day 3, the flurries do not increase steadily across time. Though there is an increase from block 1 to block 2, the remaining blocks are relatively stable; the total increase from block 1 to block 6 is 0.4 flurries per time block. Analysis of simple effects of Day found a significant effect at time block 1 [F(1.89, 34.73) = 3.73, p = .036].

The 3-way interaction is depicted in Fig. 12a through 12c. On Day 1, the frequency of flurries increase for both males and females. The rate for females is higher for all time blocks and the increase is more rapid. There is an increase in flurries for Day 2, but not as steep a slope. Flurries for females decrease from block 3 to block 5, and then increase rapidly to block 6. Flurry rates for males increase steadily from block 1 to 6. The pattern for males and females on Day 3 is different from Days 1 and 2; there is no steady increase for females. They increase from block 1 to block 3 and then exhibit a steady decline to a level lower than block 1. Males increase only slightly on

FIGURE 12A

FREQUENCY OF FLURRIES

Day 1

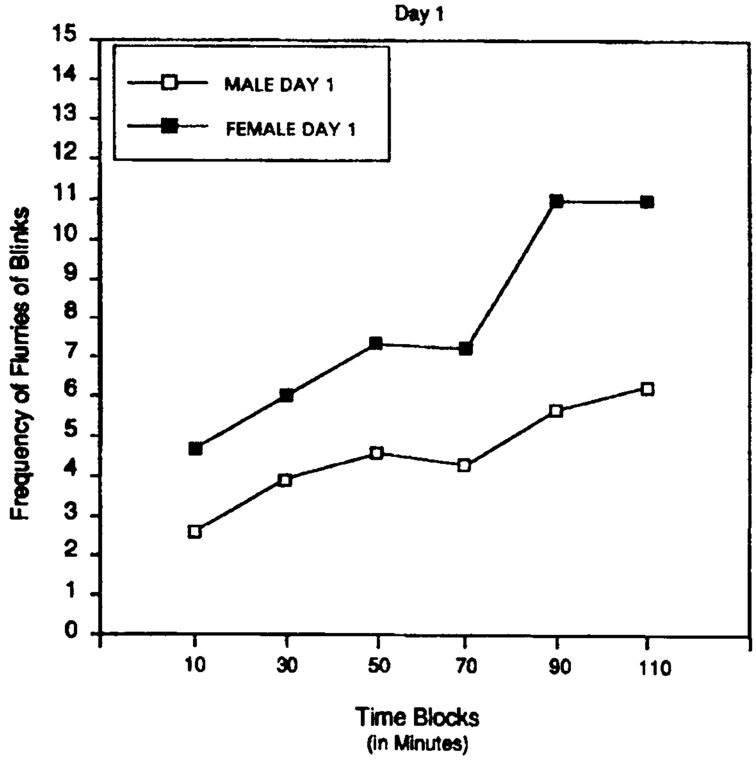


FIGURE 12B

FREQUENCY OF FLURRIES

Day 2

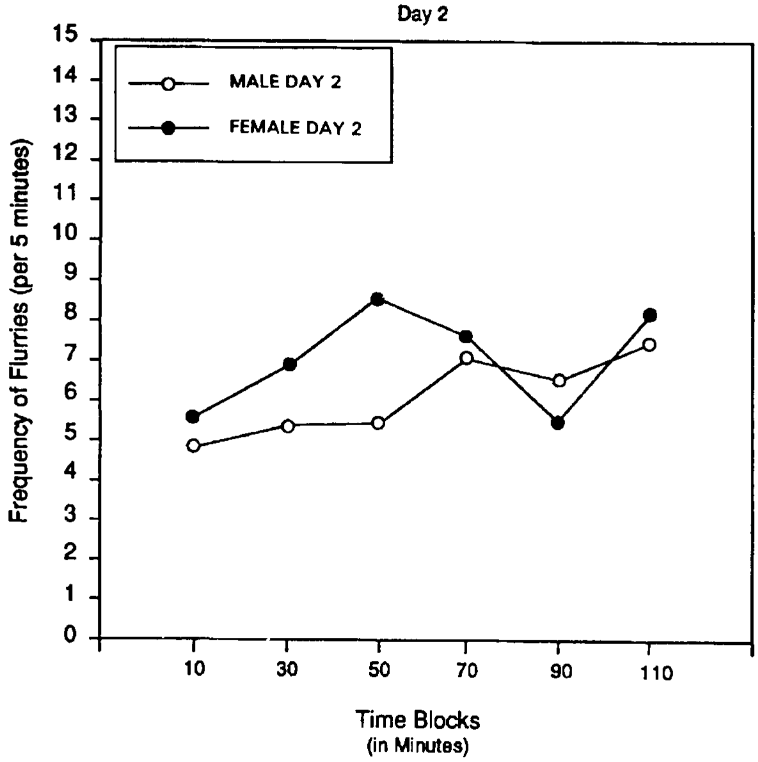
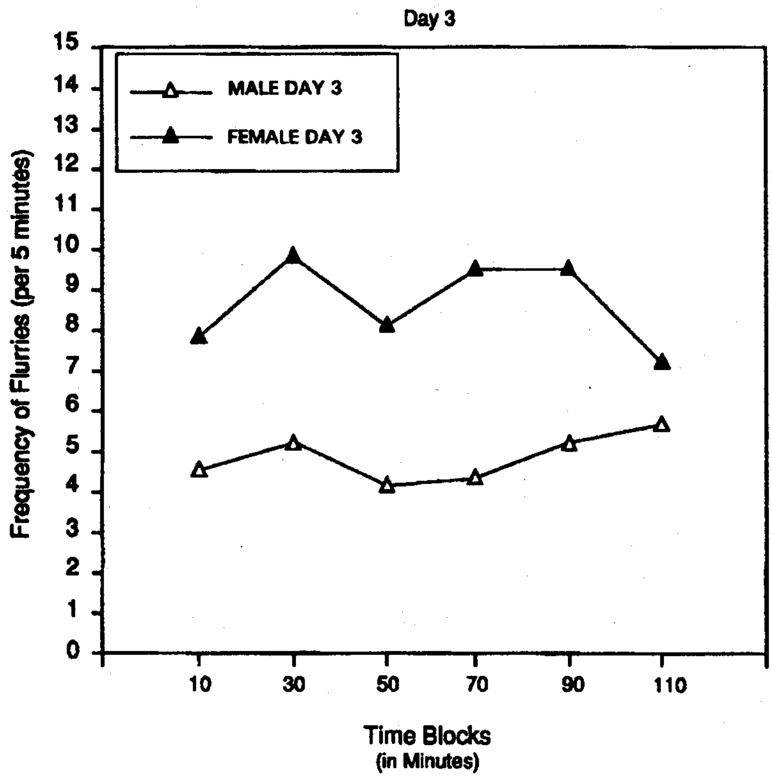


FIGURE 12C
FREQUENCY OF FLURRIES



Day 3. Analysis of the simple effects of Day X Gender at TOT found a significant effect at time block 5 [F(1.95, 35.28) = 6.04, p = .006] as well as a Day X TOT for females [F(6.4, 100,68) = 3.21, p = .008].

Since total number of blinks demonstrated a significant TOT effect, and since flurries also frequently showed a TOT effect, we expected that frequency of blinks that were part of a flurry might show an increase, purely as a function of the above 2 significant TOT effects. We thus expressed blinks contained in flurries as a percentage of all blinks occurring during the time period. This seemed to us to be an effective way of partialing out the significant blink frequency as a function of TOT effect.

Percent of blinks that are a part of a flurry. Flurries are expressed as a percentage (the number of blinks included in flurries divided by all blinks during that period, multiplied by 100). There is a significant main effect of Gender [F(1,18) = 5.23, p = .03], as shown in Fig. 13. Females have a significantly higher percentage of blinks contained in flurries than do males (Male Mean = 25.01, Female Mean = 38.09).

There is a significant main effect of time on task [F(3.8, 68.31) = 5.10, p = .001], shown in Fig. 14. The percentage of blinks that are a part of a flurry increased over time. The increase is greatest between block 1 and 2. The paired comparison between block 1 and 2 found a highly significant result [F(1,18) = 16.38, p = .001]. Between block 2 and 4 there is no increase. From block 4 to block 6 the steady increase resumed. The overall linear trend is significant at the .001 level.

There is also a significant Day X TOT interaction [F(6.4, 115.23) = 2.93, p = .01], shown in Fig. 15. The percentage of flurries is lowest on Day 1, block 1 and steadily increases through block 6, with only a slight dip in block 4. Day 2 and Day 3 start at the same level, and increase slightly through block 2. At block

FIGURE 13

PERCENT OF BLINKS THAT ARE A PART OF A FLURRY

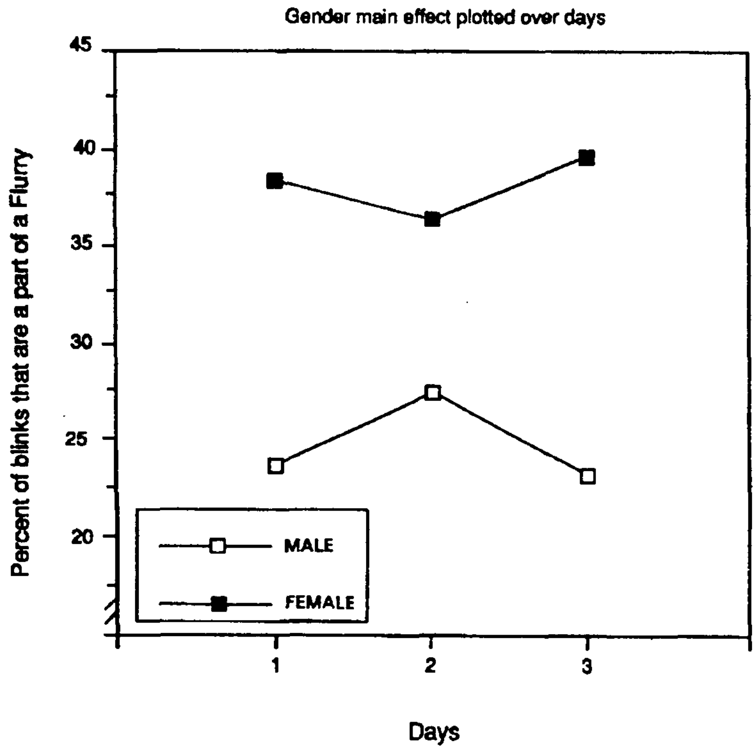


FIGURE 14

PERCENT OF BLINKS THAT ARE A PART OF A FLURRY

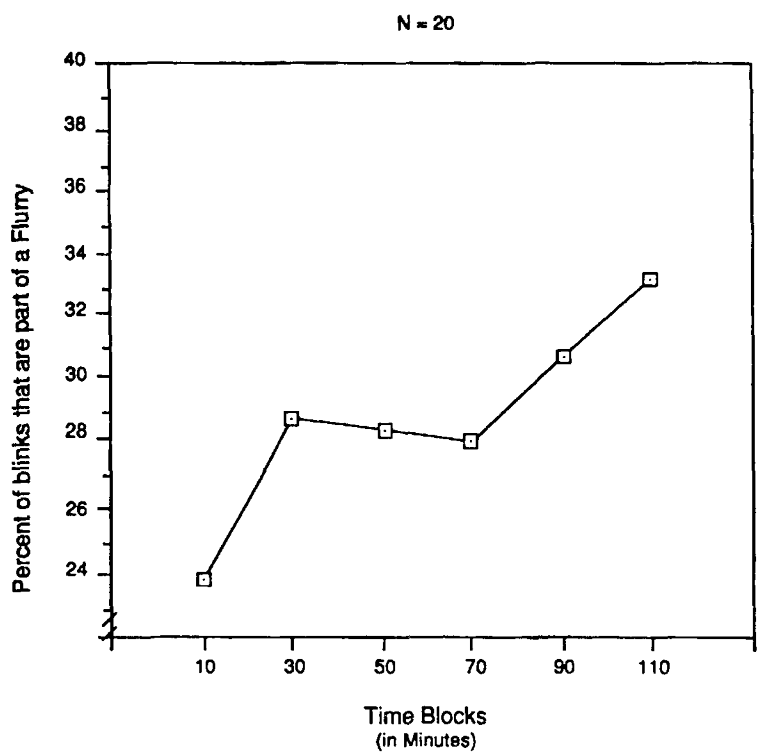
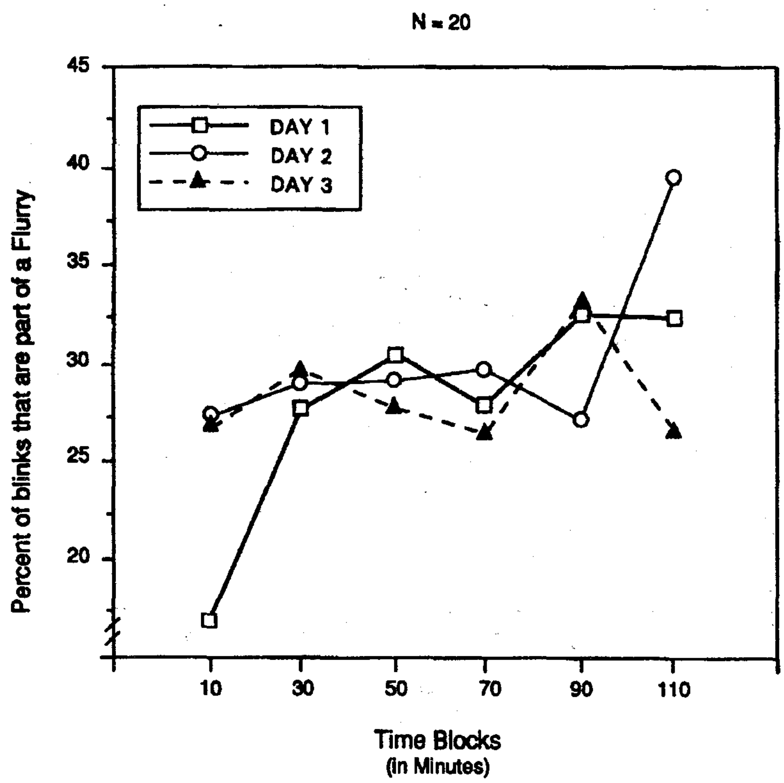


FIGURE 15

PERCENT OF BLINKS THAT ARE A PART OF A FLURRY



3, Day 2 continues to increase slightly, while Day 3 decreases. The percentage of flurries for Day 2 drops to its lowest level in block 5 and then sharply increases to its highest level in block 6. Day 3, on the other hand, rises to its highest point in block 5 and then decreases to the same level as in block 1. Analysis of the simple effects of Day found a significant effect at time block 1 [$F(1.95, 35.16) = 4.69, p = .016$]. Simple effect of TOT at Day 1 [$F(3.64, 65.56) = 5.53, p = .001$] and TOT at Day 2 [$F(3.69, 66.59) = 3.73, p = .01$].

Corrected blink rate. Since both frequency of flurries and percent of blinks that are a part of a flurry demonstrated significant TOT effects, it was possible that the significant blink rate effect could be attributed to the increase of blinks that are a part of a flurry. To evaluate this possibility, we corrected blink rate by excluding all but the first blink that was part of a flurry in the corrected blink analysis. To examine the influence of flurries on the overall blink rate, the number of blinks that were a part of a flurry was subtracted from the total blink rate; then the frequency of the occurrence of flurries was added to the result. This corrected blink rate reflected the blink rate as if each group of blinks that made up a flurry were counted as 1 blink. There was a significant TOT effect, as shown in Fig. 16. Blink rate, corrected for flurries, increases from minute 30 through 90, with a drop for the last period analyzed. The pairwise comparisons found no significant time block to time block increases.

Eye closures. The eye closure measure was collapsed over the first 3 and last 3 time blocks to create a first- and last-half measure. This was done because closures occurred very infrequently during the first 2 time blocks. There were no significant main effects. There was a significant Day X Gender interaction [$F(1.95, 35.17) = 4,18, p = .02.$]. As shown in Fig. 17, the number of closures increase steadily from Day 1 to Day 3 for males, but decrease for females from Day 1 to Day 2, and remain at the same level for Day 3.

FIGURE 16

CORRECTED BLINK RATE

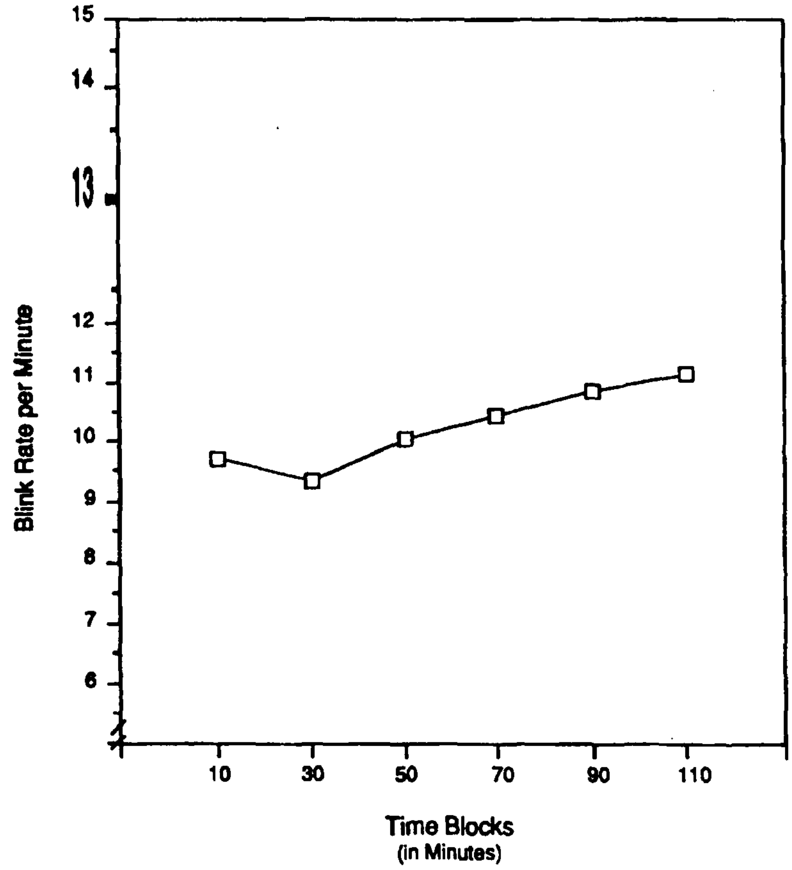


FIGURE 17

EYE CLOSURES

Day X Gender

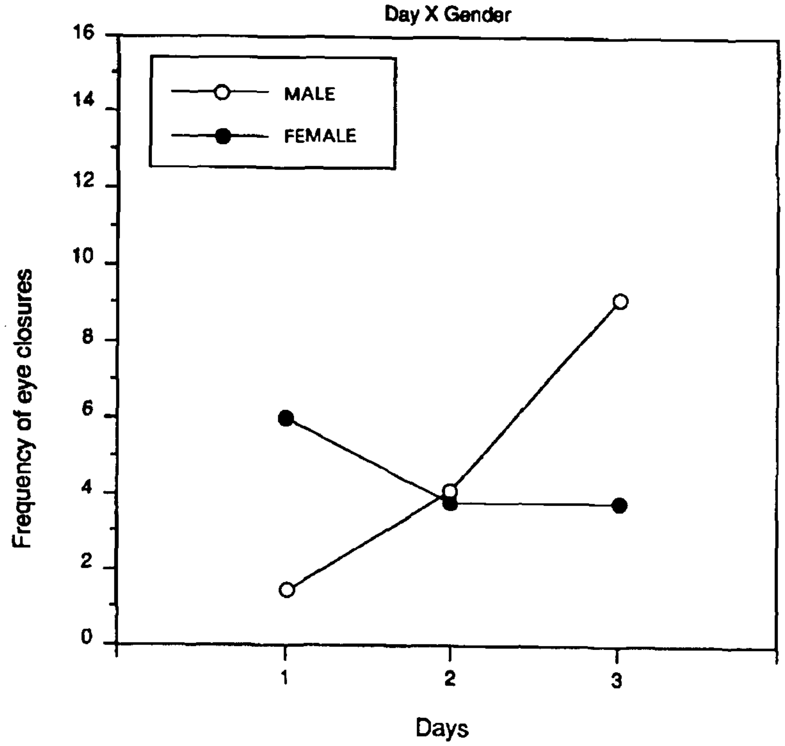
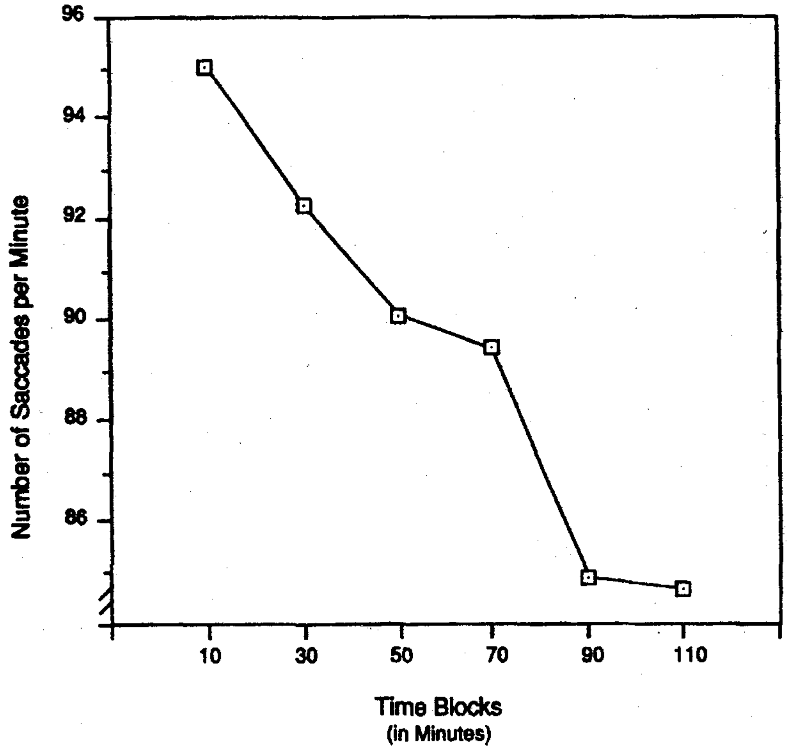


FIGURE 18

SACCADE RATE

N = 19



Analysis of simple effect Gender found a significant increase for males across days [F(1.87, 31.85), p = .002], but not for females. There is also a significant difference between the mean for males and females at Day 1 [F(1, 17) = 6.21, p = .02] and at Day 2 [F(1,17) = 17.59, p = .001].

SACCADE MEASURES

Saccades/Horizontal Eye Movements

The data from each horizontal eye movement measure (saccade rate, median fixation duration, median saccade amplitude, long duration fixation pauses) were subjected to a between-within analysis of variance. The results of each test was subjected to the Greenhouse-Geisser adjustment to the degrees of freedom. The reported F values are for this adjustment, except where specifically noted. Where main and interaction effects were significant paired, comparisons were made using the Scheffe' criterion. Only subjects who completed all 3 days were used in this analysis (20 of 26 subjects completed all 3 days).

There were no significant Gender main effects found for any of the horizontal eye movement measures.

Saccade rate. A significant time on task effect was found for saccade rate [F(3.34, 53.5) = 6.64, p = .0004]. As seen in Fig. 18, saccade rate decreases as a function of TOT, as originally hypothesized. The pairwise comparisons found a significant decrease between block 4 and 5 [F(1,17) = 7.44, p = .014]. The overall linear trend is significant at the .0002 level.

There were no significant Day effects [F(1.54, 26.22) = 0.17, p = 0.79] nor any significant interactions for either the Gender or TOD factors.

Median fixation duration. There was a significant time on task effect for the median fixation duration measure [F(3.52, 59.9) = 2.83, p = .04]. As shown in

FIGURE 19

MEDIAN FIXATION DURATION

N = 19

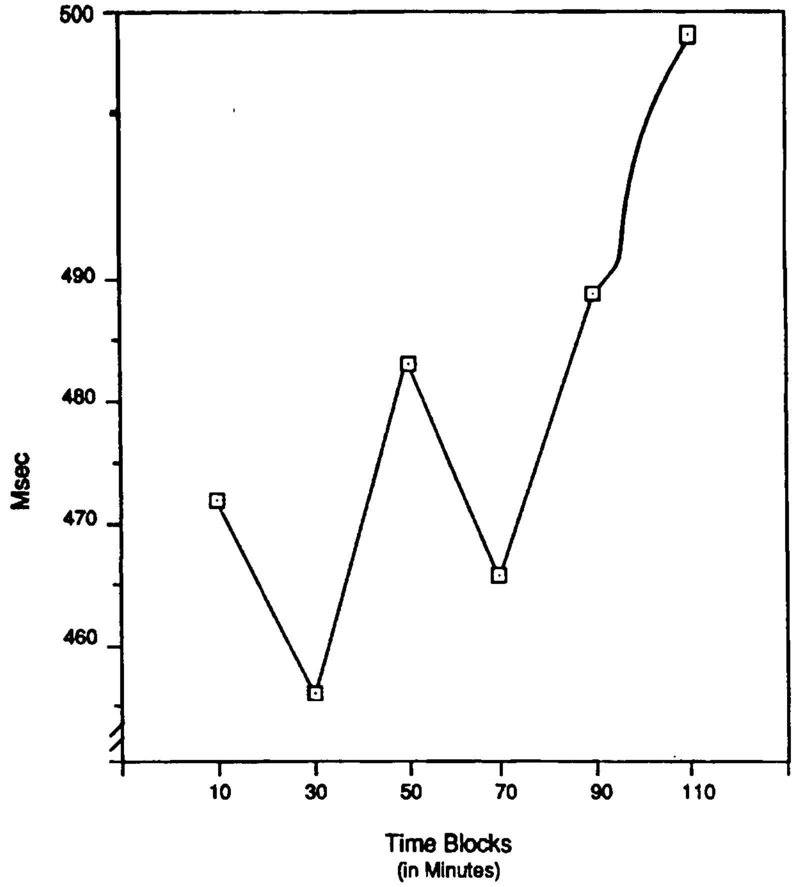


FIGURE 20

MEDIAN SACCADE AMPLITUDE

N = 19

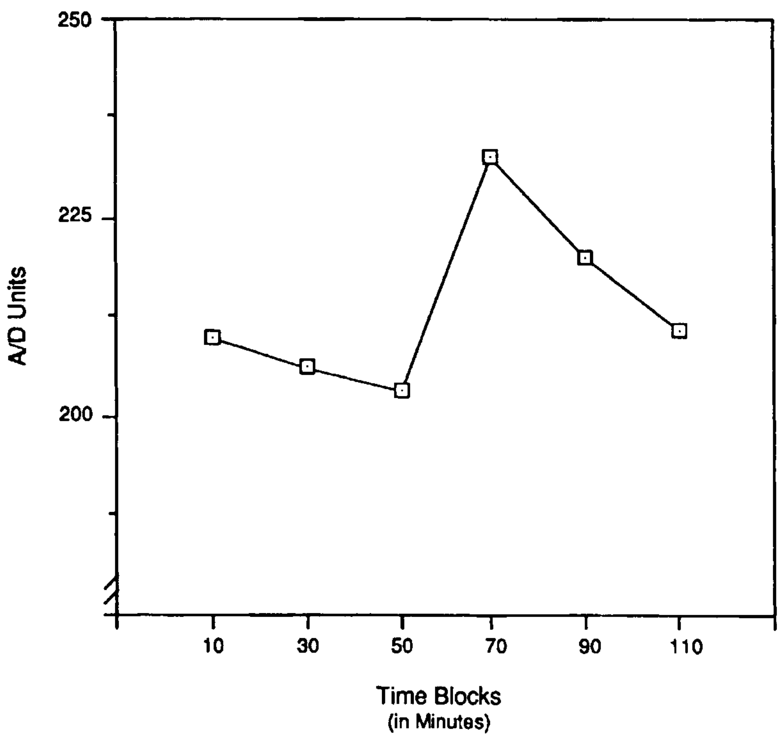


FIGURE 21

MEDIAN SACCADE AMPLITUDE

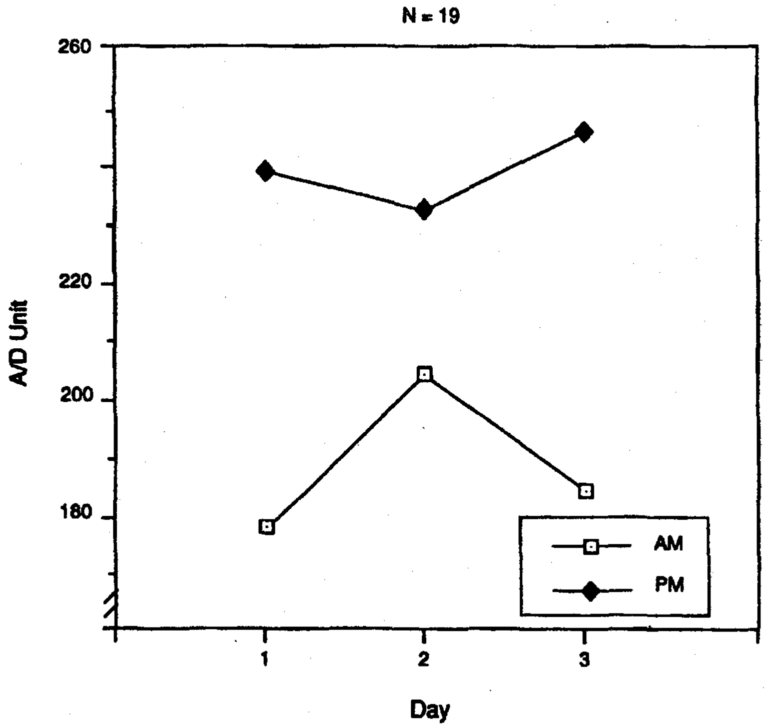


FIGURE 22

LONG DURATION FIXATION PAUSES

(Fixation pauses greater than 2 seconds)

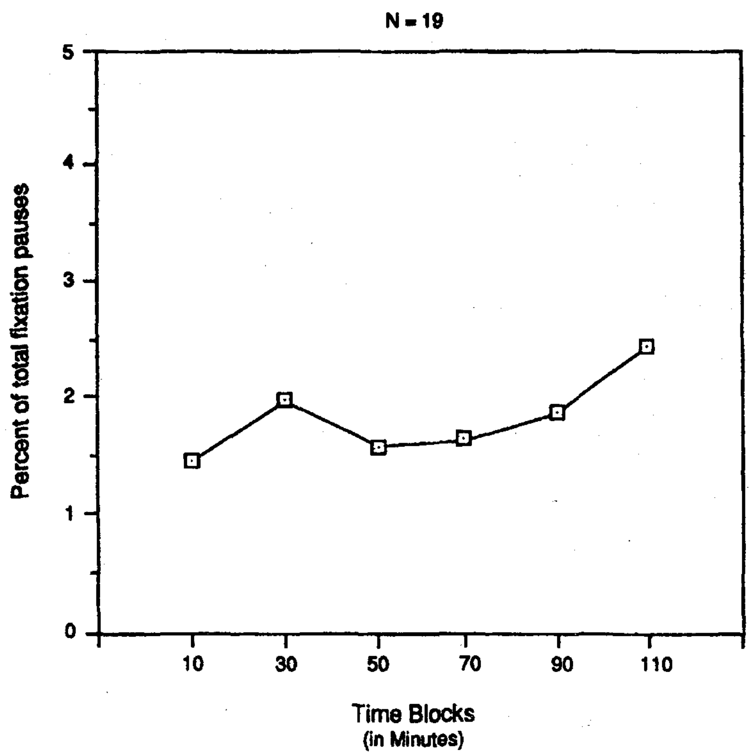


Fig. 19, there is an increase over time, but it does not look as linear as some of the other measures. The linear trend is, however, significant at the .007 level.

Median Saccade Amplitude. There is a significant TOT main effect [F(3.24, 55.05) = 12.05, p < .001], shown in Fig. 20. The amplitude decrease from 10 minutes into the tasks until the 50 minutes block, then increases dramatically from 50 to 70 minutes into the task. Pairwise comparisons found the increase between block 3 and 4 to be highly significant [F(1, 17) = 39.01, p < .000], and the decrease between block 4 and 5 significant at the .003 level [F(1, 17) = 12.2, p < .003]. Median Saccade amplitude continued to decrease at block 6.

There is a significant TOD effect [F(1, 11) = 6.12, p = .03]. The mean morning amplitude is significantly lower than the afternoon amplitude. (AM mean = 188.87 and PM mean = 238.53). The TOD effect is plotted over days in Fig. 21.

Long duration fixation pauses. The percentage of fixation pauses greater than 2 seconds also shows a significant TOT effect [F (2.76, 56.87) = 2.96, p = .05] (Huynh-Feldt). As shown in Fig. 22, the percentage of long duration fixation pauses increases slightly, but significantly over time. The pairwise comparisons finds a significant increase between block 5 and 6 [F (1, 17) = 5.03, p = .04]. The overall linear trend is significant at the .03 level.

DISCUSSION

The results for the 13 variables evaluated are summarized in Tables 1 and 2. As suggested in the Results section, a straightforward analysis in which the 4 manipulated variables were all part of the ANOVA (time on task; day; Gender; Time of Day) could not be done. As is apparent from Table 3, depicting the distribution of experimental runs for the 20 subjects for whom data were available for all 3 days, Gender and Time of Day are inextricably confounded.

Since both Gender (G) and Time of Day (TOD) were discriminators for some of the measures, we chose the expedient of conducting 2 ANOVA's for each dependent measure, 1 ANOVA using Gender, the other Time of Day as the variate of interest. These 2 measures are obviously confounded and we decline to attibute significant effects obtained with either of those variables to that variable alone. Also, the number of subjects for whom the TOD variable could be evaluated was only 13, while the Gender variable included data from 19 or 20 subjects. Thus, the degrees of freedom for the former condition was smaller than for the G effect. This makes for additional difficulty in determining which of the 2 variables was the more important.

One other restriction needs to be taken into account before discussing results. A number of measures are correlated, thus if one is significant, the other is also likely to be significant. However, since the correlation between variables seldom approaches 1.0 and since the pattern of results associated with TOT, D, and TOD may discriminate between measures, we nevertheless conducted these analyses. The fact that measures were correlated somewhat inflates the occurrence of significant results. We nevertheless chose p < .05 as the acceptable level of significance.

It is apparent that the time on task (TOT) measure generated significant results for all but 3 of the 13 dependent measures evaluated. Day (D) produced no main effects while G and TOD produced 1 and 2 significant results respectively. The number of significant interactions was reasonably small, 2 dealing with Day x Gender, 1 dealing with Day by TOD, 3 with D x TOT in the Gender and 1 with D x TOT for the TOD analysis 2 triple interaction for D x T or x G and 1 for D x T or x TOD.

BLINK MEASURES

1. Blink rate:

Blink rate showed a significant and linear increase as a function of TOT. This increase in blink rate over time is consistent with the literature. Table 5 identifies a few studies demonstrating increases in blink rate as a function of TOT. In each case, only the first author of multiple author studies is identified. In the present study, blink rate increased from a mean of 12.4 per minute during minutes 10-15 of task performance to 16.2 per minute during minutes 110-115. This is an increase of approximately 30% over a 1 hour 40-minute period, an increase somewhat less than might have been expected by extrapolating from

TABLE 5

TIME-ON-TASK, INCREASE IN BLINK RATE

Author	Nature of Task	Duration (hrs)	% increase
Buettger 1923	reading	4	200-300
Carpenter 1948	vigilance	2	47
Haider* 1976	driving sim.	4	80-100
Hoffman 1946	reading	1	71
		4	268
Luckiesh 1937	reading, light intensity	1	27
		2	79
		3	257
Morris 1984	flight sim.	4	268
Mourant 1981	reading CRT	2	33
Pfaff 1976	driving, auto	3	167
Stern 1976	driving, sim.	0.5	31
Tinker 1945	reading	0.5	38

*only the first named author of the article is identified

the results presented in Table 5. However, our first evaluation occurred after 10 minutes of task performance. Had we used the initial 5 minutes of task performance as our "base" measure, the results might be concordant with those reported in the literature.

It would be nice to be able to say that the increase in blink rate is purely a TOT or "fatigue" phenomenon. However, a number of other variables also affect blink rate. Before turning to these other variables we will briefly review a series of studies that have demonstrated increases in blink frequency as a function of TOT.

Table 5 demonstrates that a variety of tasks, where duration exceeds half an hour, cause significant increases in blink rate. Thus, driving performance (an automobile, a truck, or an airplane simulator), vigilance task performance (Mackworth Clock test), reading, and reading from a CRT, all lead to increases in blink frequency ranging from 30 to 300%. Studies demonstrating this effect date back to at least 1895, when Katz, using himself as subject, demonstrated increases in blink frequency while reading. He attributed the increase to "retinal fatigue" but also reported that requiring the subject to make frequent changes in accommodation and vergence produced increases in blinking. Our finding of a 30% increase in blink frequency over the 1 hour 40-minute period elapsing between the first and last 5-minute samples evaluated is on the "conservative" side of the changes reported in Table 5.

Not all studies in which subjects were required to perform for extended periods produced increases in blink rate. Carmichael and Dearborn (1947) had subjects read for a 6-hour period. No significant increases in blink rate were obtained for either college students or high school students reading both easy and difficult text in hard copy or microfilm format. These authors compared their results to those of Hoffman (1946), who in a study preliminary to the Carmichael and Dearborn study, had used the same equipment with students reading for a 4-hour period. Hoffman had obtained significant increases in blink rate after the initial hour of reading (see Table 5). The major difference between these 2 studies was that in the Carmichael and Dearborn study, tests of comprehension (12-13 per 6-hour reading period) occurred

TABLE 6

TASK (DIFFICULTY) AND BLINK RATE

Author	Tasks compared	Effect obtained
Carmichael 1947	reading	N
Clites 1935	logical probs, ment. arith., vis. perception	Y
Gille 1977	# copying, ment. arith., solving	Y
Gregory 1952	non-visual task	Y
Haider 1976	sim. driv. - 3 level diff.	Y
Hare 1971	viewing slides-affect	Y
Holland 1975	count b'wd, memory, rest	Y
King 1957	dynamon, tens. level	Y
Lovaas 1960	dynamon, tens. level	Y
Luckiesh 1937	light intens., ment. arith reading, conversation	Y
Peterson 1931	reading, unoccupied	Y
Poulton 1952	visual tracking	Y
Schuri 1981	voc. and quiet prob.solv.	Y
Stern 1984	pilot vs. copilot A/C	Y
Telford 1933	men. arith., rest.	Y
v. Cramon 1980	resting, reading, listen, question, discuss	Y
v. Cranach 1964	"social", "non-social"	Y
Watanabe 1980	angular displacement, target	Y
Wilson 1993	pilot high & low workload	Y
Wood 1983	problem solving, easy, diff	Y

after every 20-25 pages of reading, a comprehension test was given at the end of the 6-hour reading period, and students were given motivating instructions. Hoffman, on the other hand, did not utilize comprehension tests, reading material was easy, pay was less, and students were not exhorted to do well. Carmichael and Dearborn came to the conclusion that well motivated subjects do not demonstrate alterations in blink rate as a function of time-on-task.

We suspect that an analysis of variance design, such as used by Hoffman (1946) with repeated measures, might have found significant increases in blink rate in their studies. We believe that the techniques used to analyze the data (critical ratios) were overly sensitive to the large individual differences in blink rate. Carmichael and Dearborn fortunately present some of their summary data (for individuals) in tables. Using their tabled values, we compared blink rate at the start of the experiment with blink rate at 1-hour intervals. There were 6 such comparisons for all reading "events" (easy and difficult; text and microfilm; college and high school subjects). There were thus 2x2x2x6= 48 ratios calculated, 40 of these were positive, 8 negative (negative indicates that blink rate was smaller later, as compared to the initial 5-minute period of reading). If there was no significant effect, one would have expected half of the 48 values to be positive and half negative. Forty of the 48 values were positive. The likelihood of this being a chance event is less than .01. We thus came to the conclusion that Dearborn and Carmichael's data demonstrate time on task effects. The average increase across all trial blocks was 14%, while the average decrease for the 8 negative values was 1.6%.

Though not stated, we suspect that they sampled their blink rates not at 30-minute intervals as suggested, but during the 5 minutes of reading immediately following each of the 13 comprehension tests.

This might well lead to a lower blink rate in its own right, since Ponder and Kennedy (1927) had demonstrated that any interruption in task performance would lead to an alteration in blink rate.

Luckiesh (1937), a lighting engineer, presented a considerable amount of data demonstrating that fatigue (as well as lighting conditions) affected blink rate, correlating an increase in blinking as a function of fatigue. Tinker (1945) and Bitterman (1945) presented evidence refuting the Luckiesh findings. Our review of the published results leads us to the conclusion that Luckiesh was correct, while his critics were in error.

Our TOT effect on blink rate is thus, at least suggestive of fatigue effects. Corroborating evidence will be elaborated in subsequent sections of this discussion.

Alterations in blink rate also occur as a function of the nature and difficulty of the task being performed. Results of some studies demonstrating this effect are presented in Table 6. There is a relationship between blink rate for visual and non-visual tasks with the more "perceptually demanding" tasks producing lower blink rates. Many authors have demonstrated that the blink rate during reading is significantly lower than during "non-reading" periods (Ponder and Kennedy, 1927). Other situations, such as solving arithmetic problems (Gille, et al., 1977), (Tanaka & Yamaoka, 1992); vocalizing during vs. quietly solving problems (Schuri and v. Cramon, 1981); social vs. non social perceptual tasks (v. Cranach, 1969); large vs. small angular gaze displacement (Watanabe, et al., 1980); being engaged in discussion vs. listening (v. Cramon, 1980); increased levels of muscle tension induced by squeezing a hand dynamometer (King and Michels, 1957; Lovaas, 1960) easy vs. difficult auditory tracking task (Gregory, 1952); all lead to higher blink rates than the comparison condition.

A number of hypotheses have been invoked to explain the increase in blink rate as a function of time-on-task. The first suggests that visually demanding tasks, such as reading, lead to blink inhibition. Thus, the increase in blinking over time is attributable to a decrease in the ability to maintain such inhibitory control over extended periods of time. A second hypothesis attributes the increase in blinking to increases in muscle tension associated with attempts to sit quietly while performing a task for extended periods of time. A third possibility is that in complex tasks, such as used in the present study, there is a reduction in task difficulty (learning effect) as a function of TOT. A reduction in the allocation of attentional resources to the task at hand would require less inhibition of blinking. The third hypothesis can be rejected, since there was no Day effect. Not only might one expect the task to become easier within a day, but one would expect some transfer from Day 1 to subsequent days. Such a transfer of training would have been manifest in a significant Day effect or an interaction involving Day. No such effects occurred. We can thus infer that the increase in blinking, as a function of TOT, is not attributable to practice effects.

This leaves hypotheses 1 and 2 to account for the obtained results. We should be able to test the second hypothesis from an evaluation of our horizontal plane head movement analysis. This analysis has not as yet been conducted.

TABLE 7

BLINK RATE AT REST PLUS OTHER CONDITION

Author	Rate rest	Task Condition	Rate
Gregory 1952	22	stylus maze	19
Harris 1966	22	muscle tension	28
Holland 1975	11	count backwards	5
Martin 1958	18	resp. questions	34
Peterson 1931	15	reading	4
v. Cramon 1980	12	discussion	27

To give credence to any of these hypotheses, it would have been desirable to have recorded blinks under "non-task" conditions to determine if task performance, in fact, led to blink inhibition. There is considerable variability in "resting" blink rates across studies. However, the majority of studies reviewed in Table 7 had higher resting blink rates than those obtained early in task performance in our experiment. It thus may not be unreasonable to suggest that performance of the ATC simulation task leads to blink inhibition. Table 7 summarizes studies in which blink rates were obtained under "resting" and at least one "task" condition.

The inhibition of blinking associated with demanding visual task performance, such as reading or piloting an aircraft, or in the present context, performing the ATC simulation task, can be accounted for by the "minimal disturbance hypothesis" suggested by Knorr (1924). This hypothesis dictates that during and bracketing saccades, there is "saccade suppression," i.e., a marked reduction in visual acuity. During and surrounding the period of a blink there is also suppression of visual information (Wibbenmeyer, Stern and Chen, 1983). The co-occurence of these 2 events then would produce the least interference with the ability to take in visual information. Knorr found that blinks are inhibited during reading and that those blinks which do occur, occur at points in time where they interfere minimally with information acquisition, such as at the end of a line of text or at the end of a paragraph. Orchard and Stern (1991) similarly report that blinks are more likely to occur in conjunction with line change saccades, and add regressive saccades and fixation pauses preceded by regressive saccades to Knorr's list. In a non-reading context Watanabe, et al., (1980) required subjects to shift gaze from a centrally presented LED to LEDs at various eccentricities, with a return to the central LED after completion of the required gaze shift. They report that most blinks occurred when gaze returned from the peripheral to the central display, i.e., few blinks occurred while the eyes were moving to the required location. They also reported that blinks were more likely to occur with larger than with small angular displacement of the eyes. Fogarty and Stern (1989) have reported similar results. Subjects required to abstract and respond to information presented at a peripheral location seldom blinked as gaze shifted to the target location and were most likely to blink as gaze was returned to the central location. These authors also report that the return from a large amplitude gaze shift (40 degrees) was more likely to lead to a blink during gaze return than a small amplitude gaze shift (15 degrees). The breakdown of such inhibitory control or the breakdown of the tight time locking between blinks and saccades as a function of time-on-task, is, in our opinion, a reasonable hypothesis to entertain further to explain the demonstrated TOT or perhaps "fatigue" effect. Bartlett (1943), in his lecture on fatigue, stated:

> "In other words, he (the fatigued subject) could, within the limits of fatigue set by the experiment, still carry out the local actions of control as well or better than ever (when task demands were altered); but he could not maintain the organized, coordinated and timed responses for more than a short period." p. 253 (material in parenthesis is ours.)

As reviewed in our Results section, we broke the total number of blinks per 5-minute period down into 2 components, namely blinks that occurred as part of and blinks independent of flurries. Both of these components increase as a function of TOT. We suspect that flurries may be associated with a "momentary" and marked reduction in blink inhibition. It is our impression that such flurries most frequently occur following the identification of infrequently occurring signals and also prior to and following periods of eye closures. These both appear to be times when attention is likely to lapse. In our review of the literature we came across 2 comments dealing with flurries. Carpenter (1948) reports that periods of blink inhibition in which subjects appeared to be staring, were sometimes followed by a "burst of blinks." Carpenter did not comment further about this phenomenon. His observation is, however concordant with ours. Frolov (1990) reports as follows:

"In tracking rare random visual signals 'volleys of aftereffects' were noticed which were the ER (eye response) at the time when the operator ended the tracking (of a dot moving across the face of the CRT in 20 seconds) and was getting ready to wait for new signals. The 'volley' indices were computed for minute-long intervals, which followed ends of tracking. These parameters were found sensitive to the complexity of the task for the subject." p. 74 (our comments in parens).

It is our impression that the "volley of aftereffects" is similar to our measure of blink flurries and that Frovlov's observation is similar to ours. Thus, one can identify 3 separate studies, all of which have observed blink flurries and have time locked then to specific events.

Increases in blink frequency, as a function of TOT, is found to be a robust phenomenon. Whether it occurs as a function of lapses in inhibitory control, or is attributed to alterations in attention or fatigue, is problematic. We believe that all 3 of these phenomena are closely related. If the increase in blinking, as a function of TOT, is due to lapses in inhibitory control, we should see an increase in the number of blinks not time-locked to saccades as a function of TOT. This analysis is proposed for future study.

2. Blink closing duration and the blink 50% window measures

Both reflect, we believe, similar aspects of blinking, namely an index of the duration for which vision is obscured by the eyelids during a blink. The actual time for which visual information is not available to the viewer during lid closures and reopening is, in part, a function of where the eyes are pointed prior to and following a blink. Under laboratory conditions where the subject is instructed to look straight ahead and the eyes are presumably at the same location preceding and following a blink, the 50% measure is a reasonable approximation of the time for which vision is obscured (Kennard & Glaser, 1964). In the present context, eye position following a blink was generally at a location other than where the eyes were pointed preceding the blink. Hacker (1962), as well as Watanabe (1980), report similar results. Thus, neither of our measures are to be taken as anything but a crude index of how long vision was obscured during a blink. The finding that eye position shifts during a blink should, in retrospect, not be terribly surprising. During a blink, vision is obscured for a definite period; during a saccade vision is also impaired (saccade suppression). It is thus reasonable for that computer between our ears to perform both functions concurrently, thereby reducing the amount of time vision is obscured.

It will be recalled that the closing duration measure is an index of the time taken from the initiation of lid closure (associated with a blink) to the point in time where the lid is fully closed, while the 50% window measure is the time between the lid reaching half the full closure distance and full closure and the point in time where the lid returns through that same level during reopening. We should point out that our algorithm for the identification of a closure-reopening as a blink requires that the 50% window measure be completed in a specifiable time frame, which, in the case of this study, was set at 300 msec. Eye position shifts during a blink and quite frequently the blink does not return to the 50% level during the reopening phase. This occurs because eye position on reopening is higher in the visual field than before closing (for example, blinks occurring as gaze returns from the keyboard back to the CRT). Thus, data had to be edited to allow the computer algorithm to identify such blinks. Such editing involved setting the initiation of blink at the level of the eye position obtained after reopening. Such editing reduced average amplitude, closing duration, and 50% window. The amount of such editing did not change appreciably across time blocks, and thus did not contribute to TOT effects. It should be pointed out that the editing function, in all cases, reduced the blink amplitude, closing duration, and 50% window duration measures. Our editing thus artificially reduced these variables. Nevertheless, our TOT variable demonstrates an increase in closing duration, and 50% window as a function of TOT. It is thus a robust effect.

The closing duration and 50% window measure both demonstrated significant increases as a function of time-on-task. Average closing duration was at its

lowest during the first time block, (10 minutes into task performance), and at its highest during the last, (the measurement obtained at minute 110). Average closing duration shifted from approximately 85 msec. to 93 msec., a shift of only 8 msec., but a reliable shift, nonetheless. We would suggest that in future studies data be sampled at least at 5 msec. intervals to allow for better temporal resolution of this variable.

Though Days did not demonstrate to be a reliable variate, we wish to point out that closure duration for the first measure on Day 1 was the shortest and increased over successive days. In general, all Day 1 average values were consistently below those for Days 2 and 3, while the latter 2 demonstrated considerable overlap.

The 50% window measure, in addition to showing the Time of Day effect demonstrated in Fig. 5 for the closing duration measure, also demonstrated a significant Day by Gender interaction. This interaction is depicted in Fig. 6. Let us, for the moment, attribute the effect to the Time of Day variable. In any case, as was true of the closing duration measure, the lowest 50% window measure was obtained at the 10-minute measurement period (mean of 122 msec.) and the highest at the last measurement period (mean of 133 msec.). The Day by Gender interaction depicted in Fig. 6 indicates that the average 50% window measure increases in a linear fashion from Day 1 to Day 3 for males, while for females (based on a smaller number of subjects), the Day 2 measure is below the other 2 days, though not reliably so. As seen in Fig. 7, the first measures of the day showed the same increase over days characteristic of the closing duration measure (though not statistically significant).

We (Bauer, et al., 1985 and Stern & Skelly, 1984) have previously demonstrated TOT effects similar to those obtained here. In the Bauer, et al., study the time period for which data was collected was 45 minutes. Subjects performed a visual or auditory temporal discrimination task. The 50% window measure changed from 133 msec. early in task performance to 148 msec. for approximately the last 5 minutes of the 45-minute task. The Stern and Skelly (1984) study, performed in a flight simulator with Air Force pilots flying a 5-hour bomber mission also demonstrated significant time-on-task effects for this measure, as well as significant effects attributable to differences in task demands on the pilot during different flight segments. For example, the pilot in command of the aircraft demonstrates significantly shorter 50% window durations than the copilot. Nature of flight maneuvers also significantly affected average window duration with "weapons delivery" and "threat avoidance" producing significantly shorter window durations than cruising at altitude or "nap of the earth" flying. The present results suggest that performing the ATC simulation task was more demanding of the participant on Day 1 as compared to successive days, or that subjects paid closer attention to task performance early on Day 1 than on subsequent days.

This measure thus appears to be sensitive to both TOT effects, as well as motivational effects. To the extent that closing duration and the 50% window measures reflect momentary reductions in motivation (also considered as momentary drops in alertness or attention to task), the monitoring of these variables should allow one to predict that if a brief stimulus requiring a response occurs in close temporal relationship to such a blink that the likelihood of a performance drop-out or "performance block" (Bills, 1931) is markedly enhanced. We should, however, point out that long closure duration blinks unfortunately do not uniquely identify the occurrence of a performance "block." We have also observed longer closing duration blinks while subjects stored and rehearsed information (Stern, 1992; Goldstein, Bauer, & Stern, 1992).

3. Blink Amplitude

Though the 50% window measures has consistently demonstrated TOT effects, blink amplitude has not done so. We are aware of one study (Morris, 1984) that found significant changes in blink amplitude as a function of TOT. That study utilized sleep deprived subjects required to fly a GAT-1 simulator over a 4-hour prescribed course. Blink amplitude significantly declined over the 4-hour task and occurred because of a partial lowering of the eyelids in fatigued subjects. It is somewhat surprising that blink amplitude does not correlate significantly with closing duration. In the present study, the correlation

between these 2 variables was 0.41, suggesting relative independence of these measures. Our surprise must be tempered by the findings of Evinger, et al., (1984) who report that the duration of the closing phase of large, as compared to small or regular amplitude blink, decreases, rather than increases. However, such large amplitude blinks "occurred only when subjects were instructed to blink or "flutter the eyelids." Duration of upper lid motion was otherwise remarkably constant in humans. A linear relationship was found in rabbit and guinea pigs (Evinger, et al., 1984). They suggest that, "The poor correlation between duration and amplitude suggested that the metrics of the lid movements were more typical of skeletal ballistic movements than of saccadic eye movements." Our results fit in well with those of Evinger, et al.

Blink amplitude analysis did not provide any significant main effects. However, the Day x TOT interaction was significant in the TOD analysis. This effect appears to be principally attributable to Day 3, when we see an increase in blink amplitude as a function of TOT, while Day 1 and 2 data show little TOT effects.

4. LCD Blinks

Long closure duration blinks were those blinks in which the 50% window exceeded 200 msec. plus manually identified blinks where the eye remained closed for less than 1 second. Closures persisting for more than 1 second are referred to as lid closures.

The analysis of LCD blinks involved combining the above 2 sets of blinks (computer and manually identified) for each 5-minute period and expressing the frequency of occurrence of such blinks with respect to all blinks occurring during that time period. This procedure was necessitated by the significant increase in blink frequency as a function of TOT. Thus, finding significant increases in LCD blinks as a function of TOT, could have been attributed to this finding. We believe that controlling for the increase in blink frequency by using the ratio measure is a procedure as effective as analysis of covariance, without making any of the assumptions underlying the latter procedure. Using this procedure, no significant TOT effect was obtained. The increase in LCD blinks over time is thus secondary to an increase in blink rate over time. Though not significant, the shift is from approximately 3% of blinks during minutes 10-15 to 5-1/2% during minutes 110-115.

5. Flurries

Flurries were defined as the occurrence of 3 or more blinks in a 3-second period. A flurry could extend for more than 3 seconds if, in succeeding seconds, the rate of 1 or more blinks per second was maintained. The analysis of flurries dealt with 2 components; namely their number per unit time, and secondly, the total number of blinks incorporated in a flurry. The latter analysis was conducted to determine the extent to which the significant increase in blink frequency, as a function of TOT, might be accounted for by changes in flurries. The flurries analysis generated 2 significant main effects; one attributable to TOT, the second attributable to Gender. The TOT effect indicates significant increases in flurry frequency as a function of TOT; the Gender effect suggests a higher rate of flurries for female subjects (remember that this effect is confounded by Time of Day) though the TOD effect was not significant. Part of the reason for lack of significance is attributable to the smaller subject pool (N=13) for the TOD, as compared to the Gender effect analysis (N=20). There was also a significant TOT by TOD interaction and a 3-way interaction involving the above 2 variables plus Gender.

Why is there an increase in flurries as a function of TOT? Do flurries occur at random time points or are they related to other events? Though not as yet substantiated by a rigorous review of the data, it is our impression that flurries do not occur at random time points. Flurries are most likely to be seen after the subject has responded to an infrequently occurring event and are seen (somewhat less frequently) preceding and/or following eye closures. They are also frequently seen at the point in time where the subject realizes that the experimental procedure has been completed. There is inhibition of blinking during the period of identifying and responding to such events. One possible rationalization for the flurry, but not our favorite one, is that these blinks occur as "catch-up phenomena" to make up for blinks missed while detecting, identifying and responding to an "event."

The rationalization we believe to be correct suggests that the flurry of blinks occurs because the subject has learned that another "event" will not occur for some time. Thus, the flurry indexes a period of reduced alertness or attention to the task. This latter interpretation is reinforced by the fact that during a flurry, one also sees little saccadic activity in the horizontal plane. Another point in time where flurries are likely to occur is preceding and following an eyelid closure. It appears as if a flurry of blinks is an attempt to ward off an eye closure. We thus suspect that a measure incorporating the concurrence of flurries and long duration fixation pauses may be a useful measure of reduced alertness.

Though not systematically studied by anyone to date, we, as well as others (Yamada, 1992), have observed flurries of blinking at the end of an experimental run. Yamada (1992), for example, had children perform a number of tasks ranging from watching a video-animation (Snoopy and Charlie Brown), performing the STROOP test and playing a video game (Nintendo Super-Mario III). He reports "Subjects' blinking was inhibited just after the initiation of each task. When the given task (was) finished, blinks occurred in bursts" (p. 4).

6. Eyelid Closures

Eyelid closures are, in the present experiment, rare events; most subjects had no closures during the first 3 time blocks on Day 1. If the eyelid remained closed for more than 1 second, such an event was identified as an eye closure (EC). Because such closures occurred relatively infrequently, data from the first 3 and the last 3 five-minute time segments were combined. We expected an increase in such events as a function of TOT. This comparison was not significant. There was, however, a significant Day effect, as well as a Day x Gender interaction. There was a significant increase in EC frequency over days. The interaction effect suggests that such an increase was characteristic of male, but not female subjects, and that females had significantly more closures on Day 1 than males and that they showed relatively little change in ECs over days. Again, it is unclear whether this is truly a Gender or TOD effect. The increase on the part of male subjects was appreciable with an average of 1.5 closures for the 30 minutes of data analyzed for Day 1 to 9.14 on Day 3. The pattern for females was an average of 6 on Day 1 and 3.9 on Day 3 (Fig. 17).

It is our impression that when ECs occurred they were most frequently seen following the making of a response, i.e., subjects took "time-out" from task performance, since they had developed the expectancy that another event requiring a response would not occur for a minute or more. The phenomenon, previously observed in conjunction with such lid closures, was also observed here, though not quantified. In a prior study (Lobb & Stern, 1986), such closures were associated with slow horizontal eye movements. Initially, one sees few horizontal eye movements during a closure. As a function of TOT, one begins to see slow rolling eye movements (SEM). These SEMs increase in angular excursion. Upon reopening of the eyes, one frequently sees a pair of saccades, suggestive of momentary spatial disorientation (where am I?), before returning to a normal pattern of saccadic activity. The present task is a visually demanding one, and as we have demonstrated before (Stern, Goldstein, & Walrath, 1984), visual tasks are less likely to have associated eye closures than comparable tasks where information is presented auditorily, rather than visually. Another probable reason for the relatively small number of eye closures obtained in this study is the fact that if a subject missed an infrequently occurring event, both a visual and an auditory signal were used to alert him/her to the event. Such alerting information is a likely contributor to the low level of closures obtained here.

II. SACCADE ANALYSIS

1. Saccade rate and median fixation duration.

There was a significant decrease in saccade rate as a function of time-on-task (TOT). The decrease in saccade frequency appears to be reasonably linear with decrements seen from the first time period evaluated. For all 3 days, the initial rate is 95 saccades per minute and drops to 84 saccades per minute at minute 110. There is thus an approximately 12% decrease in saccades over the 2-hour period.

Associated with a decrease in saccade rate, as a function of TOT, should be an increase in average fixation pause duration. This was indeed the case. However, the average fixation durations displayed in Fig. 19 are markedly shorter than those based on extrapolation from the saccade frequency data. For example, the mean saccade rate at minute 10, as depicted in Fig. 18, is 95 per minute. There was thus, an average of 94 fixation pauses per minute, with a calculated average fixation pause duration of 638 milliseconds. Note that the median fixation duration depicted in Fig. 19 is approximately 475 msec., a discrepancy of some 163 msec. Interpolating in the other direction, one would expect 126 saccades per minute if the average intersaccade interval is 475 msec. What accounts for these discrepant results?

2. Fixation Pause

There is a paucity of research dealing with changes in fixation pause duration as a function of TOT. It is clear from the literature that in such complex tasks as scanning an instrument panel during flight, neither the search pattern nor the time the eyes dwell at a particular location are random processes (Ellis and Stark, 1968).

Statistical dependencies independent of the placement of specific instruments are the rule, rather than the exception; most subjects demonstrate specific patterns of search activity while dealing with component aspects of the task of piloting an aircraft (Stoliarov personal communication, 1991).

A number of studies have used secondary task technology to evaluate aspects of work load associated with a visual task on scanning performance. The results of such studies, while tangential to the present study, provide some relevant information. Tole, et al., (1982) demonstrated, in an aircraft piloting task, that fixation pause durations increase as a function of task difficulty of the secondary task, a verbal loading task. Scanning behavior was also detrimentally affected with novice pilots showing greater restrictions of scanning behavior than skilled pilots, as secondary load increased. Another finding important for us was that as loading increased, so did dwell time (fixation duration) on each instrument. The increase, in some cases, was large enough to prompt these authors to refer to the subject as "staring" at the display. Stares are defined as dwell times in excess of 5 seconds. The highest secondary load condition produced increases in stares ranging from 3.7 to 23.4% for the 6 subjects for whom data is presented (mean increase of 12.7% S.D. 7.7).

There is a vast literature dealing with fixation pauses associated with reading. Hoffman (1946) had subjects read without interruption for 4 hours. He reports a significant decrease in both the number of fixations and the number of lines read within the first 30 minutes of reading performance. Variability (SD) of number of fixations per line increased; the increase was significant after 2 hours of reading. Average fixation pause duration (interpolated from saccade frequency data, Fig. 4) was 280 msec. at the first sample and 316 msec. at the 4-hour completion time sample, approximately a 13% increase (compared to a 6 to 8% increase in our study).

Carmichael and Dearborn (1947) report (using critical ratio statistics) mean differences in saccade frequency of 3 of 12 comparisons for both of their reading tasks. The general pattern appears to be one of high reading efficiency for the first 5 minutes of the reading task. There is a marked drop at the 30-minute measurement period with relatively asymptotic performance from the second through the sixth hour of reading. It should be remembered that reading was interrupted after every 20 to 25 pages for comprehension checks. Though these authors minimize the importance of the obtained TOT effects, to those looking for such effects, there is abundant suggestive evidence that, had they used more appropriate statistical tools (available at the time) they would have obtained a TOT effect.

The germain references for our evaluation deal with the Tole, et al. studies, which suggest a decrease in saccades and an increase in fixation pauses, especially long duration fixation pauses as secondary task demands increase. If we can, instead of invoking secondary task demands (which require the allocation of attentional resources) conceive of TOT effects as requiring greater allocation of attentional resources to the primary task, or the allocation of attentional resources to counteract boredom, fatigue, physical discomfort, daydreaming, and other variables associ-

ated with TOT (which can also be conceived of as secondary tasks, albeit not under the control of the experimenter) we would expect both a decrease in saccade frequency and an increase in long duration fixation pauses (Tole's stares).

Our results are concordant with both of these expectations. We obtained a significant decrease in saccade frequency (Fig. 18) a significant increase in fixation duration (Fig. 19) and a significant increase in long duration fixation pauses (Fig. 22).

The median fixation duration measure, and to a lesser extent saccade rate, show the same phenomenon described for the saccade amplitude measure, namely an unexpected change at the 70-minute measure. In the case of fixation duration, the 70-minute time block has returned to a level of fixation duration intermediate to that seen for the 10- and 30-minute blocks, and again with an increase for the last 2 sampling periods. Saccade rate shows a steady linear decline over time blocks 10, 30, and 50, and rate at 90 minutes is a direct extrapolation from that line. Thus, at 70 minutes, there is an inhibition of this "decay" function. Again, we are at a loss to account for these effects.

It is our contention that fixation durations are not normally distributed, that in the performance of this task it is logical to expect a bimodal distribution of fixation durations. When the operator finds an infrequently-occurring event, such as 2 aircraft sharing the same altitude, he/she has to respond to that event and then wait for an update of the display to determine if the aircraft are on a collision course or not, flying in the same direction. After making this decision, the operator takes appropriate action by moving a cursor over 1 of the planes and requesting an altitude change. The display is updated every 6 seconds. An "efficient" viewer thus should be able to make the appropriate decision within 6 seconds. One may thus be required to maintain fixation at a specific location for up to 6 seconds. Moving a cursor over an aircraft ID also requires fixating the ID segment while aligning the cross hairs with the segment. This also may require a relatively long fixation pause (relative to median fixation durations of 475 msec.) Add to that the hypothesis that, as a function of TOT, there should be an increase in the frequency of "blocks" (Bills, 1931). It is our expectation that such blocks should be accompanied by LDFPs. We would further expect an increase in the occurrence of eyelid closures with concurrent inhibition of horizontal saccades as a function of TOT. Combining all, the distribution for these variables is likely to be bimodal. There are thus a number of reasons that fixation pauses should not be normally distributed. Our solution to the problem of non-normality was to use median fixation pause duration as one of our dependent measures, since medians are less affected by "extreme" values.

To separately capture the other end of the bimodal distribution, we identified a category of fixations we labeled "long duration fixations" (LDFs). Before turning to this measure, we would like to point to one other "apparent" discrepancy between the saccade rate and median fixation duration measures. The saccade rate measure appears to be linear, with roughly the same increment in saccade frequency between successive time blocks. The line of best fit for the median fixation duration measure suggests that for the first 4 measurement periods (or the first 70 minutes of task performance), there is a relatively small increase in this variable, with most of the change occurring over the last 2 time periods evaluated. Thus, these 2 measures appear to deal with different components of changes in processing ability as a function of TOT. Further analyses for disentangling some of these discrepancies will be performed. Saccades and fixation pauses associated with responding to the infrequently-occurring events and responding to alerting instructions when an event has been missed will be analyzed separately from the "normal" search operation.

3. Saccade Amplitude

Saccade amplitude appears to be affected by TOT effects. We identified 2 studies demonstrating significant amplitude changes as a function of TOT. Malmstrom, Randle and Murphy (1981) obtained a linear decrease in saccade amplitude of 0.29 degrees per minute, as well as a significant shift in accommodation (0.11 diopters per minute) as subjects performed 2 scanning tasks, each for a total of approximately 6.5 minutes. In the task demonstrating saccade amplitude effects, subjects were required to

track a sinusoidally-moving target (horizontal plane at 0.4 hz, 18 degree amplitude) for 13 consecutive 30-second periods. They obtained a 9% loss of range with extent of eye movements decreasing from 15.4 to 14.3 degrees over the 6.5-minute period. No phase lag changes of eye position with respect to target position were obtained. The authors conclude that the significant change in saccade amplitude cannot be accounted for on the basis of refractoriness of the muscles controlling eye movements, and thus suggest that we are dealing with a CNS mediated change.

May, et al., (1985) recorded eye movements while subjects performed non-visual tone counting tasks differing in complexity. Eye movements were studied under a "free viewing condition," i.e., no restriction on eye movements, and a condition where subjects were required to shift gaze between 2 LEDs 20 degrees apart, with a gaze shift required every 5 seconds. Spontaneous (non-stimulus triggered) saccades decreased in amplitude as a function of TOT. Of further interest, though not directly relevant here, is their reporting a decrease in saccade amplitude as a function of task difficulty (with no effect on saccade velocity). There was thus limited support for evaluating saccade amplitude effects before considering saccade duration or velocity effects.

We should preface discussion of our results with a brief comment on other variables that can contribute to finding changes in saccade amplitude as a function of TOT. The major variable of concern is head position relative to the CRT. In the studies identified above, this was controlled for by immobilizing the head. If the head is free to move, as is true of our experimental situation, then changes in saccade amplitude may well be secondary to changes in head position. Moving away from the CRT display would decrease the visual angle subtended by the display and result in decreased saccade amplitude. Moving the head closer to the display would have the opposite effect. The chair on which our subjects sat was not attached to the floor, but subjects were not likely to move it during an experiment. Subjects could, however, shift their position on the chair. They could sit up straight and move their upper body toward the CRT; they could also slouch in the chair, thus moving their eyes further away from the CRT. Such body movements might account for the obtained changes in saccade amplitude as a function of TOT. We suspect, however, that this is not the case. We would consider such movements as unwanted "noise" in our signal analysis, since there is no reason for them to be time-locked to events occurring on the CRT, i.e., we would not expect shifts in body position to occur at specific times, but suspect that they would occur quite randomly, with perhaps an increase in frequency over time.

Our finding of a significant TOT effect for saccade amplitude (Fig. 20) adds to this literature. Our effect, however, is somewhat more complicated than that described by May, et al., as well as Malmstrom, et al. Their task duration was considerably shorter than ours and the discrepant results may be a function of this variable alone. We find that the best fit for our obtained results is not linear, but quadratic. We see a steady decrease in saccade amplitude from the 5-minute sample, starting at minute 10 and continuing to minute 50. A marked increase in amplitude is found at minute 70, with a further decline over the next 2 samples. Our results do not disagree with either of these studies, since their TOT periods were less than 50 minutes in duration. In addition to a significant amplitude effect, we also obtained a significant Time of Day (TOD) effect (Fig. 21), with significantly greater amplitude saccades for the afternoon, as compared to the morning sessions. Since this effect is confounded by Gender, we will not discuss it further.

It would be convenient if we had a straightforward (or even convoluted) explanation for the complex effect obtained. We do not believe that it is a random effect, since a number of other variables also show a discontinuity at this same point in time (the 70-minute and following samples). Another reason for suspecting that it is a real effect is that the samples taken at minutes 90 and 110 do not drop to the levels one might have projected from the slope of the curve connecting the 10-, 30- and 50-minute samples. We, however, have no rationalization for this effect.

4. Long Duration Fixation Pauses (LDF)

We defined LDF as fixation pauses equal to or longer than 2 seconds. This duration was selected because on Day 1, for the earliest measure (10 min.)

the percentage of fixations meeting this criterion was less than 1% of all fixations. As indicated earlier, some of these LDFs are associated with responding to the "infrequently" occurring events. Since there was an equal number of such events in each of the 5-minute periods for which data were abstracted, the LDFs attributable to this effect are approximately the same for each of the periods sampled. As Fig. 22 demonstrates, the increases in LDF occur quite late in the 2-hour period. The 90- and 110-minute samples appear to be the major contributors to this effect. The MDF measure reflects a similar pattern, with the last 2 time periods acting as the major contributors to the significant increase obtained. We doubt that the demonstrated MDF effect is a reflection of the LDF phenomenon, since the latter fixation pauses contributed little to the definition of MFPD, i.e., LDFs never exceeded an average of 4% of all fixation pauses, it should thus have little effect on the median value.

We attribute both the increase in MFPD and in LDF to "fatigue" effects. Compensatory effects, such as enhanced effort or energy expenditure to maintain performance at a high level, are no longer adequate to compensate for fatigue effects. We suspect that if events requiring rapid responding occur at points in time where either of these 2 types of fixation pauses occur, the likelihood will be great that such events will be missed.

GENERAL DISCUSSION

Our analysis of gaze control variables provides abundant evidence of time-on-task (TOT) effects. There is a significant increase in blink rate, closing duration, 50% window duration, flurries, and percent of blinks that are part of a flurry. Saccade rate decreases significantly and fixation pause duration, as well as long duration fixation pauses increase significantly as a function of TOT. We interpret these TOT effects as suggesting alterations in attention to the task at hand. We have previously suggested and presented evidence relating to the occurrence of blinks to points in time where the operator momentarily takes time-out from taking in and/or processing information. The increase in blink rate may thus indicate points in time where the operator shifts attention from task requirements to other events, be they externally triggered or internally triggered by intrusive thoughts. We have suggested that such intrusions occur as a function of a breakdown in "inhibitory control" and may be further reflected in the occurrence of flurries of blinks independent of, or in conjunction with, long duration fixation pauses, and with the occurrence of blinks in the absence of saccades.

The finding that the nature of the blink changes, as a function of TOT, is suggested as indicating fatigue effects. Other reasons for the increase, such as alterations in task demands as a function of learning, were ruled out because of a lack of such an effect over days. One finding, though not statistically reliable, suggests that motivational variables may also have to be invoked. For both the blink closing duration and the 50% window measures, it appears that there are consistent changes from Day 1 to Day 2 to Day 3 for the initial data set (starting at minute 10). These consistent changes involve an increase in both measures over days. Thus, though objective task demands did not change from Day 1 through Day 3, the changes in blink closing duration suggest that less effort is expended in task performance early on each successive day. We interpret this to mean that though task performance, as measured by missed signals, does not change appreciably across days, subjects tend to allocate fewer attentional resources to the task. The significant D x G interaction for the 50% window measure suggests that this motivational variable discriminates between males and females (or perhaps with TOD). Males show the increase in the 50% window measure across days, while females do not. The same Gender effect pattern is manifest in the eye closure measure, with males showing a significant increase over days, while females remain more constant.

These results suggest that males showed greater decrements in motivation (as reflected in these 2 measures) over the 3 days of task performance then was true of females.

One consistent difference between males and females was in frequency of flurries, with females generating significantly more flurries than males. We earlier suggested that flurries do not occur randomly, but appear to occur following responding to an infre-

quently occurring event (regardless of whether the response occurred because the subject detected the event or whether she was cued to respond to the event) as well as preceding and/or following eye closures. If flurries can be interpreted as a procedure for attempting to fight-off or delay "attentional blocks" then the data would fit in with the above hypothesized differences between the male and female study participants.

There are some puzzling results, which at this time defy our interpretation. A number of measures suggest "recovery" from TOT effects at 70 minutes into task performance. Though most of these effects were not statistically reliable, we are puzzled by the fact that 4 of our measures appeared to demonstrate this effect. For the blink closing duration measure, there is a decrease in closing duration from minute 50 to 70, while all other adjacent pairs show an increase. The 50% window duration shows a similar phenomenon for Days 1 and 2 of task performance. Fixation duration demonstrates a decrease from the 50- to the 70-minute time block, followed by a large increase and saccade amplitude, a significant increase from minute 50 to 70 with subsequent decreases, though the 90- and 110-minute amplitudes still remain above those for minutes 10, 30, and 50.

This study was designed to identify gaze control measures sensitive to lowered levels of alertness associated with time-on-task performance. The results clearly demonstrate that as alertness declines across an extended period of monitoring a simulated ATC display, there are aspects of the gaze measures that exhibit consistent changes across the subject population. Monitoring performance also declined across that time period (Schroeder, Touchstone, Stern, Stoliarov, and Thackray, 1994). It is our hypothesis that when individuals exhibit the eye movement patterns suggestive of "momentary" lapses in attention they should miss information presented during that time. We further hypothesize that such lapses increase in frequency as a function of time-on-task and that there are marked individual differences in the occurrence of such lapses. Additional research is needed to verify these hypotheses, the first by introducing visual and/or auditory stimuli requiring a decision and response during periods when gaze control variables suggest that attention is compromised.

The ability to utilize these findings in an operational sense also resides on the capability of monitoring the gaze patterns in a less obtrusive manner, one that is independent of any attachment of electrodes or requiring the wearing of a special monitoring device that may in and of itself be fatigue inducing. There is a capability that is now available through LC Technology for monitoring eye movements through use of a fixed camera located below a visual display. Additional research is needed to determine if that capability can be used in a more applied setting to assess changes in gaze patterns and identify periods when operators are less alert and attentive. Planning is underway for developing a study that will address some of these issues and concerns.

This area of research addresses a long standing concern associated with the ability of human operators to monitor complex displays and maintain performance and alertness over extended periods of time. Current concerns associated with the negative impacts of fatigue on performance are evident in ongoing research within several transportation modalities (trucking, aviation and air traffic control). It is also an issue in a variety of other job settings where the task of the human operator involves a high level of scanning and maintenance of attention in monitoring system performance. Despite the high level of concern within present systems, concerns associated with the role of fatigue in attention maintenance is likely to increase as systems become more highly automated and the role of the human operator involves a greater monitoring component. Thus, additional research is needed to develop more effective state of the art techniques that could be implemented in a relatively unobtrusive manner to identify circumstances under which the operator is functioning at a reduced level of alertness and is more susceptible to lapses of attention or episodes of what is often referred to as "micro sleep." If that is possible, various alerting or coping techniques could be developed and implemented to reduce error conditions associated with the lowered attentional levels.

REFERENCES

Andresen, B., Seifert, R., Lammers, C., and Thom, E. (1988). Spontaneous blink rate, schizophrenia, and schizotypal personality. *Journal of Psychophysiology*, 2, 129-130.

Appel, V.H., McCarron, L.T. and Manning, B.A. (1968). Eyeblink rate: Behavioral index of threat? *Journal of Consulting Psychology*, 15, 153-157.

Bagley, J. and Maneus, L. (1979). Effect of awareness as an indication of cognitive load. *Perception and Motor Skills*, 49, 591-594.

Bahill, H.T. and Stark, L. (1975). Overlapping saccades and glissades are produced by fatigue in the saccadic eye movement system. *Experimental Neurology*, 48, 95-106.

Bartlett, F.C. (1943). Fatigue following highly skilled work. *Proceedings of the Royal Society*, 13, 131, 247-257.

Bauer, L.O., Strock, B.D., Goldstein, R., Stern, J.A. & Walrath, L.C. (1985). Auditory discrimination and the eyeblink. *Psychophysiology*, 22, 636-641.

Bills, A.G. (1931). Blocking: A new principle of mental fatigue. *American Journal of Psychology*, 43, 230-245.

Bills, A.G. (1943). *The Psychology of Efficiency*, New York: Harper and Brothers Publication.

Bills, A.G. and McTeer, W. (1932). Transfer of fatigue and identical elements. *Journal of Experimental Psychology*, 15, 23-36.

Bitterman, M.E. (1945). Heart rate and frequency of blinking as indices of visual efficiency. *Journal of Experimental Psychology*, 35 279-292.

Buettger, W. (1923). Concerning blink frequency as a measure of visual fatigue: effect of light intensity and color on fatigue. Dissertation abstract: Medical Faculty Georg-August University, Gottingen, Germany

Carpenter, A. (1948). The rate of blinking during prolonged visual search. *Journal of Experimental Psychology*, 38, 587-591.

Carmichael, L. and Dearborn, W.F. (1947). *Reading and Visual Fatigue.* Boston: Naughton Mifflin Co.

Clites, M.S. (1935). Certain somatic activities in relation to successful and unsuccessful problem solving. *Journal of Experimental Psychology*, 18, 708-724.

Collewijn, H., van der Steen, J. and Steinman, R.M. (1985). Human eye movements associated with blinks and prolonged eyelid closure. *Journal of Neurophysiology*, 54, 11-27.

Crommelinck, M. and Roucoux, A. (1976). Characteristics of cat's eye saccades in different states of alertness. *Brain Research*, 103, 574-578.

Dichgans, J., Nauck, B. and Wolpert, E. (1973). The influence of attention, vigilance and stimulus area on optokinetic and vestibular nystagmus and voluntary saccades. In Zikmund, V. (Ed.), *Oculomotor systems and brain functions.* London: Butterworth, 280-294.

Dwelshauvers, G. (1928). The education of automatism. *Psychologie et vie*, 1, 11-14.

Ellis, S.R. and Stark, L. (1986). Statistical dependency in visual scanning. *Human Factors, 28*, 421-438.

Evinger, C., Shaw, M., Peck, C.K., Manning, K.A. and Baker, R. (1984). Blinking and the associated eye movements in humans, guinea pigs, and rabbits. *Journal of Neurophysiology*, 52, 323-339.

Fisk, A.D., and Schneider, W. (1981). Central and automatic processing during tasks requiring sustained attention: A new approach to vigilance. *Human Factors*, 23, 737-750.

Fogarty, C. and Stern, J.A. (1989). Eye movements and blinks: Their relationship to higher cognitive processes. *International Journal or Psychophysiology*, 8, 35-42.

Frank, M.C., and Kuhlo, W. (1970). The effect of alcohol on saccadic eye movements in man. *Archive Psychiatrie und Nervenkranken*, 213, 238-245.

Frolov, M.V. (1990). *Monitoring the functional state of a human operator.* Moscow: Nauka Publishers.

Giambra, L.M., and Quilter, R.E. (1987). A two-term exponential functional description of the true course of sustained attention. *Human Factors*, 29, 635-643.

Goldstein, R., Bauer, L.O., and Stern, J.A. (1992). Effect of task difficulty and interstimulus interval on blinking and cardiac activity. *International Journal of Psychophysiology*, 13, 111-117.

Gregory, R.L. (1952). Variations in blink rate during non-visual tasks. *Quarterly Journal Experimental Psychology*, 4, 165-169.

Hacker, W. (1962). On modifications of the so-called spontaneous eye blink during work. *Probleme und Ergebnisse der Psychologie*, 5, 7-43.

Haider, E. and Rohmert, W. (1976). Blink frequency during 4 hours of simulated truck driving. *European Journal of Applied Psychology*, 35, 137-147.

Hare, R., Wood, K., Britain, S., Shadman, J. (1971). Autonomic response to affective visual stimulation. *Psychophysical*, 7, 408-417.

Harris, C.S., Thackray, R.I., and Shoenberger, R.W. (1966). Blink rate as a function of induced muscle tension and manifest anxiety. *Perceptual and Motor Skills*, 22, 155-160.

Hoffman, A.C. (1946). Eye movements during prolonged reading. *Journal of Experimental Psychology*, 36, 95-118.

Holland, M.K. and Tarlow, G. (1975). Blinking and thinking. *Perceptual and Motor Skills*, 41, 403-406.

Jantti, V., Lang, A.H., Keskinen, E., Lehtinen, I., and Pakkanen, A. (1983). Acute effects of IV alcohol on saccadic eye movements and subjective evaluation of intoxication. *Psychopharmacology*, 79, 251-255.

Katz, R. (1895). Blinks as a measure of visual fatigue. *Klinische Monatblaetter fur Augenheilkunde*, 154-157.

Kennard, D.W. and Glaser, G.H. (1964). An analysis of eyelid movements. *Journal of Nervous and Mental Disorders*, 139, 31-48.

King, D.C., and Michels, K.M. (1957). Muscular tension and the human blink rate. *Journal of Experimental Psychology*, 53, 113-116.

Knorr, A. (1924). Contributions to knowledge about eye blinks under normal and pathological conditions. *Abhandlungen an der Gesamtgeboten der Medizin*, 25, in Hacker.

Lille, F. and Cheliout, F. (1982). Variations in diurnal and nocturnal waking state in Air Traffic Controllers. *European Journal of Applied Physiology*, 49, 319-328.

Lobb, M.L. and Stern, J.A. (1986). Pattern of eyelid motion predictive of decision errors during drowsiness: oculomotor indices of altered states. *International Journal of Neuroscience*, 30, 17-22.

Lovaas, I.O. (1960). The relationship of induced muscular tension, tension level and manifest anxiety in learning. *Journal of Experimental Psychology*, 59, 145-152.

Luckiesh, M. and Moss, F. (1937). *The Science of Seeing.* New York: Dvan Nostand Co., Inc.

Mackworth, J.F. (1964). Performance decrement in vigilance, threshold, and high-speed perceptual motor tasks. *Canadian Journal of Psychology*, 18, 209-223.

Manzer, C.W. (1927). An experimental investigation of rest pauses. *Archives Psychology*, 90, 1-84.

Martin, I. (1958). Blink rate and muscle tension. *Journal of Mental Science*, 104, 123-132.

Malmstrom, F.V., Randle, R.J., Murphy, M.R., Reed, R.E., and Weber, R.J. (1981). Visual fatigue: The need for an integrated model. *Bulletin of the Psychonomic Society*, 17, 183-186.

May, J.G., Kennedy, R.S. Williams, M.C., Dunlap, W.P. and Brannan, J.R. Eye movements as an index of mental work load. *Final Report Contract F49620-85-C-0121*, Phase I, Topic #174.

Morris, T.L. (1984). EOG indices of fatigue-induced decrements in flying related performance. USAFSAM Technical Report, Brooks AFB.

Mourant, R.R., Lakshmanan, R., and Chantadisai, R. (1981). Visual fatigue and CRT display terminals. *Human Factors*, 23, 529-540.

Orchard, L. & Stern, J.A. (1991). Blinks as an index of cognitive activity during reading. *Integrative Physiological and Behavioral Science*, 26, 108-116.

Oswald, I. (1962). *Sleeping and Waking.* Amsterdam: Elsevier.

Peterson, J. and Allison, I.W. (1931). Control of the eye wink mechanism. *Journal of Experimental Psychology*, 14, 144-154.

Ponder, E. & Kennedy, W.P. (1927). On the act of blinking. *Quarterly Journal of Experimental Physiology.* 18, 89-110.

Simonov, P.V. and Frolov, M.V. (1984). Psychophysiological control of the functional state of the human operator. *Soviet Psychology*, 23, 68-87.

Stave, A. (1977). The effects of cockpit environment on long-term pilot performance. *Human Factors*, 19, 503-514.

Stern, J.A., Beideman, L. and Chen, S.C. (1976). Effects of alcohol on visual search and motor performance during complex task performance. In M. Horvath (Ed.) *Adverse Effects of Environmental Chemicals and Psychotropic Drugs*. Amsterdam: Elsevier Scientific, 2, 53-68.

Stern, J.A., Bremer, D.A. and McClure, J.N. Jr. (1974). Analysis of eye movements and blinks during reading: Effects of valium. *Psychopharmacologia*, 40, 170-175.

Stern, J.A. and Skelly, J.J. (1984). The eye blink and work load considerations in Proceedings of the Human Factors Society 28th Annual Meeting, Santa Monica, CA: *Human Factors Society*, 942-944.

Tanaka, Y., Yamaoka, K. (1992). Blink activity and task difficulty. Paper presented at Pavlovian Society of North America, October 9-12, Westwood, CA.

Thackray, R.I. and Touchstone, R.M. (1989). Effects of high visual taskload on the behaviours involved in complex monitoring. *Ergonomics*, 32, 27-38.

Tinker, M.A. (1945). Reliability of blinking frequency employed as a measure of readability. *Journal of Experimental Psychology*, 35, 418-424.

Tole, J.R., Stephens, A.T., Harris, R.L. Sr., and Eprath, A.R. (1982). Visual scanning behavior and mental work load in aircraft pilots. *Aviation Space and Environmental Medicine*, 54-61.

von Cramon, D. (1980). Spontaneous eyeblink: mirror of psychosomatic activity. *Medizinische Psychologie*, 6, 123-139.

von Cranach, M., Schmidt, R. and Vogel, M.W. (1969). Concerning the relationship between blinks and gaze shifts. *Psychologische Forschung*, 33, 68-78.

von Gille, H.G., Otto, G. and Ullsperger, P. (1977). Change in EEG, HR, and blrink rate during performance of four levels of conentration - performance test, alertness, and time estimation. *Zeitschrift fur Psychologie*, 185, 397-413.

Watanabe, Y., Fujita, T. and Gyoba, J. (1980). Investigation of blinking contingent upon saccadic eye movements. *Tohoku Psychologica Folia*, 39, 121-129.

Weiner, E.A. and Concepcion, P. (1975). Effects of affective stimuli on eye blink rate and anxiety. *Journal of Clinical Psychology*, 31, 256-259.

Wibbenmeyer, R., Stern, J.A., and Chen, S.C. (1983). Elevation of visual threshold associated with eyeblink onset. *International Journal of Neurosciences*, 18, 279-286.

Williams, H., Lubin, A. and Goodnow, J.J. (1959). Impaired performance with acute sleep loss. *Psychological Monographs*, 73, 484.

Wood, J. and Hassett, J. (1983). Eye blinking during problem solving. *Psychophysiology*, 20, 18-20.

Yamada, F. (1992). Inhibition of blink rate and enhancement of Fm-theta (frontal mid line) rhythm during playing a video game. Paper presented at Annual Meeting of Society for Psychophysiological Research, October 16, San Deigo, CA.

Zee, D., Chu, R., Leigh, J., Savino, P.J., Schatz, N., Reingold, D. and Cogan, D.G. (1983). Blink-saccade synkinesis. *Neurology*, 33, 1233-1236.